Agricultures' adaptation to water management policies and global change : the interest of economic programming models

Nina Graveline

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Nina GRAVELINE
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Adaptation de l'agriculture aux politiques de gestion de l'eau et aux changements globaux : l'apport des modèles de programmation mathématique

Directeur de thèse : **Jean-Christophe BUREAU**

Jury

M. Javier Calatrava, Professeur, Economia, y politica rural, Univ. Politécnica de Cartagena	Rapporteur
M. Hubert Stahn, Professeur, GREQAM, Université d'Aix-Marseille	Rapporteur
M. Pierre Mérel, Professeur, Groupe d'Economie agricole, ETH Zürich	Examinateur
M. Thierry Rieu, UMR « Gestion de l'Eau, Acteurs, Usages, AgroParisTech	Examinateur
M. Jean-Daniel Rinaudo, Economiste, Nouvelles Ressources et Economie, BRGM	Examinateur

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Adaptation de l'agriculture aux politiques de gestion de l'eau et aux changements globaux : l'apport des modèles de programmation mathématique

Nina Graveline

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Abstract

This thesis develops and discusses agricultural-supply modeling approaches for representing the adaptation of farming to global changes and water policies: their effects on agricultural economics and water resources comprise critical information for decision makers. After a summary and a review chapter, four essays are presented.

The first essay describes a representation of the behavior of ten typical farms using a risk linear programming model connected to a plant-soil-hydrodynamic model chain, to assess the future level of nitrate contamination in the upper Rhine valley aquifer. The baseline, liberal, and interventionist scenarios for 2015 all result in lower nitrate concentrations.

The second essay explores the effects of the economic uncertainty of global changes by means of a Monte Carlo approach distinguishing various levels of dependence on uncertain parameters. Analyses for a nitrate-oriented and a water-use model (in Alsace and southwestern France) show that the environmental objectives can be targeted with sufficient confidence.

The third essay develops a flexible specification for positive mathematical programming - constant elasticity of substitution with decreasing returns - to explore how irrigated farming adapts to increased water scarcity in Beauce, France. The possibility of adjusting the application of water per hectare accounts for about 20% of the response.

The last essay presents the development of a holistic hydro-economic model of Beauce ś agriculture and aquifer under climate-change uncertainty, so as to evaluate various water policies, as well as the open-access case, up to the year 2040. The results show that the baseline policy is more cost-effective than the other instruments tested (tax, transfer, etc.).

Keywords: agriculture, water scarcity, nitrates, uncertainty, adaptation, mathematical programming, hydro-economic modeling

Résumé étendu en français

L'agriculture fait face à des contraintes croissantes sur l'usage des intrants et des ressources naturelles tels que l'azote, les pesticides et l'eau, en raison de l'accroissement des préoccupations environnementales et de la demande en eau notamment. Face à ces contraintes, les exploitations agricoles et le secteur agricole doivent adapter leurs pratiques et leurs productions. D'un point de vue réglementaire, la Directive Cadre sur l'Eau exige que des programmes de mesures soient dimensionnés en fonction des scénarios tendanciels de pollution ou de pression quantitative sur les masses d'eau afin d'atteindre les objectifs de "bon état écologique". Dans ce contexte, la modélisation des choix futurs de production et d'utilisation des intrants est un enjeu important pour pouvoir informer les décideurs de l'évolution tendancielle et de l'impact de politiques de l'eau sur l'économie agricole et sur l'état des ressources en eau.

Cette thèse développe et discute différentes méthodes et applications qui s'attachent à représenter le comportement des agriculteurs face à de contraintes croissantes sur l'utilisation des intrants, eau et azote. Ces méthodes sont largement basées sur le principe de modèlisation micro-économique par programmation mathématique et nous expliquons en quoi il apparaît plus pertinent de faire ce choix plutôt que celui de l'économétrie. L'intégration des modèles économiques avec des modèles ou données bio-physiques (agronomique et hydrogéologique) est explorée pour mieux représenter le système hydro-économique et compléter les évaluations. L'enjeu méthodologique du développement de modèles de programmation est de rechercher le meilleur compromis entre une représentation suffisamment contrainte pour répliquer la situation observée et suffisamment flexible pour pouvoir simuler des changements significatifs.

La thèse comporte une synthèse globale, une revue de littérature sur les approches de programmation économique pour la gestion de l'eau par l'agriculture ainsi que 4 essais qui sont principalement tirés d'articles parus ou en cours de publication.

Le premier chapitre présente un travail qui a permis d'estimer le niveau de contamination en nitrate dans l'aquifère du Rhin supérieur en France et en Allemagne. Les concentrations en nitrates sont largement dues à l'agriculture qui s'est intensifiée dans les années 70. L'approche de modélisation par type d'agriculteurs permet de représenter 80% de la surface agricole utile de la zone d'infiltration de l'aquifère. La programmation linéaire avec prise en compte du risque (MOTAD) est retenue pour représenter le comportement de plus d'une dizaine de types d'agriculteurs céréaliers, laitiers, viticulteurs et exploitations

diversifiées. Les résultats sont extrapolés à l'échelle des petites régions agricoles et servent de paramètres d'entrée à une chaîne de modèles qui comporte un modèle de croissance de plante, de bilan azoté et un modèle hydrodynamique pour représenter les transferts et concentrations de nitrate dans l'aquifère. Trois scénarios d'évolution sont construits: un scénario dit tendanciel, un autre dit libéral, et un dernier dit interventioniste. Leur impact sur les pratiques d'utilisation de l'azote et de l'eau, les assolements et la production agricole est simulé. Les surfaces en maïs baissent dans les trois scénarios tout comme les concentrations en nitrate. Celles-ci décroissent moins, étonnement, dans le scénario interventioniste qui soutient le développement de biocarburants de première génération. L'intérêt d'une taxe sur l'utilisation d'azote et d'une autre sur les reliquats azotés est évalué, mais les résultats indiquent que des niveaux de taxe très élevés doivent être atteints pour que ces taxes soient efficaces.

Le second chapitre s'intéresse à l'effet de l'incertitude liée aux changements globaux sur l'utilisation et la pollution de l'eau par l'agriculture. Cette analyse se base sur des simulations Monte Carlo à partir des modèles développés au chapitre précédent et d'autres qui représentent l'agriculture irriguée du système Neste dans le Sud-Ouest de la France. L'incertitude sur les prix des produits et des intrants ainsi que la disponibilité et le besoin en eau des plantes sont caractérisés pour chacun des trois scénarios tendanciel, libéral et interventioniste en spécifiant des variables de rang 1 et 2 qui permettent une corrélation de l'incertitude pour certaines variables. Les résultats suggèrent que l'objectif de réduction des nitrates c'est-à-dire la pollution par les nitrates à l'horizon 2015 présente relativement peu d'incertitude et que des programmes de mesures peuvent donc cibler cet objectif avec confiance. Cette approche peut également être considérée comme une réponse partielle à la critique souvent faite à la programmation linéaire, de son comportement en sursaut ("jumpy behavior") dans la mesure où elle produit un ensemble de réponses contrairement à une réponse unique dans le cas de simulations déterministes.

Le troisième chapitre traite de l'adaptation de l'agriculture à la baisse de la disponibilité en eau à partir du cas de l'agriculture irriguée en Beauce (France). L'adaptation de l'agriculture est analysée à partir de trois marges d'adaptation: la marge supra-extensive (passage de l'irrigation au pluvial), la marge extensive (passage d'une culture intensive en eau à une autre moins intensive) et la marge intensive (changement de la dose d'eau apportée par culture et par unité de terre). Une spécification flexible basée sur les principes de programmation mathématique positive (PMP) et à élasticité de substitution constante et rendements marginaux décroissants est adoptée afin de représenter ces trois marges. Trois variantes sont développées, elles sont calibrées avec des données de réponse agronomique du rendement à la dose d'eau. Certaines répliquent le profit tandis que d'autres sont calibrées sur l'élasticité-prix de l'offre. Nous simulons l'effet de contraintes croissantes de la disponibilité en eau, avec ou sans possibilité de transfert inter-régional. Les impacts économiques sur l'agriculture (hors industrie) d'une réduction de 30% de la disponibilité en eau sont modestes. Environ 20% de la réponse est attribuable à la marge d'ajustement intensive (ce résultat est sensible à la valeur de l'élasticité de substitution) et montre ainsi l'intérêt de modèles qui permettent cette adaptation; ce qui n'est pas le cas avec les modèles linéaires.

Le dernier chapitre illustre l'interêt d'un couplage dynamique entre modèle économique et bio-physique pour améliorer la représentation du système hydro-économique. Il présente le développement d'un modèle hydro-économique dit "holistique" de l'agriculture et de l'aquifère de Beauce afin d'évaluer différentes politiques de l'eau et le cas de l'absence de régulation (open access) jusqu'èn 2040. L'incertitude sur les variables climatiques ainsi que le changement climatique sont considérés grâce à des simulations Monte Carlo. Elles montrent que la politique actuelle de gestion de l'eau entraînerait des niveaux piezométriques inférieurs aux moyennes historiques pour certaines des régions de la nappe. Un indicateur coût-efficacité permet de confirmer la supériorité de la politique actuelle face aux autres instruments testés (taxe piezométrique "ambiante", transferts, calcul des droits en fonction de niveaux historiques, ressources de substitution). Les résultats suggèrent que l'effet d'internalisation de la baisse des niveaux pièzométriques à travers les coûts de pompage n'est pas suffisant pour rendre le cas sans régulation équivalent à la situation de régulation actuelle.

Plusieurs perspectives de ce travail sont discutées dont la question de l'amélioration des représentations du comportement relatif à l'usage des intrants par les agriculteurs notamment dans des situations qui sont éloignées de la situation de référence. L'enjeu de l'intégration du risque et de l'incertitude dans les modèles en considérant un possible accroissement des incertitudes dans le futur est également discuté. Dans une perspective d'appui aux politiques publiques, nous discutons enfin de l'interêt des modèles hydro-économiques en France et de la nécessité de considérer plusieurs enjeux environnementaux simultanément.

Preambule

This PhD thesis is based on research that I developed - intermittently- between 2004 and 2013 within the context of several research projects. They all focused on the evolution and adaptation of agriculture to environmental and economic scenarios, and to water policies. After I graduated in 2004, I took an engineer research position at BRGM and have been working there since then on various topics with a main theme on water management. In 2011, after a 5-month stay at the University of Davis, California, as part of a research collaboration with P. Mérel, at the department of agricultural and resource economics, I finally decided to go back to some of my first works to deepen my research on the topic of agricultural input use and adaptation in a global change context. This experience triggered my decision to start a PhD in parallel of my work at BRGM.

The first chapter is issued from the MoNit project ("Modélisation de la pollution des eaux souterraines par les nitrates dans la vallée du Rhin supérieur") funded by the European Community, the Région Alsace and the LUBW in Germany. A part of the second chapter (Neste case study) derives from an IRSTEA project funded by the French Ministry of Agriculture. The remaining work presented in this chapter has been supported by the research direction of BRGM. My stay at the University of California, Davis has been funded by the French National Research Agency ANR, via the Carnot Fund. The writing of the review chapter as well as the development of the hydro-economic model of the last essay were partly supported by the research direction of BRGM.

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I strongly believe I would not have made it in the first place, if I had not done this first 5-month stay in Davis at the Department of Agricultural and Resources Economics in 2011, followed by a one-month stay in 2012. Richard Howitt made these stays possible in an exceptional setting and Pierre Mérel accepted to invite me and work with me. Thank you for this. The intense and fruitful collaboration during this first 4 months with Pierre has been a crucial trigger to this project. I am therefore deeply grateful for the time Pierre spent working with me, despite his teaching and research workload. I really learned a lot by his side. Thanks for the introduction to LaTex. Thank you also for the cooking and running experiences. Big Thanks go to Antoine who made my stay very nice, friendly and sporty and even philosophical. Thank you so much for the laTex assistance. Thanks also to Josué Medellin-Azuara for our interesting lunch-discussions about hydro-economic modeling in California.

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Main scientific publications[1]

Journal publications

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[1]* corresponds to publications that are not connected to works presented in this thesis

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Conference publications

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Graveline, N., Casper, M., Grimm-Strele, J., Koller, R., Lambrecht, H., Rinaudo, J., and Van Dijk, P. (2006). Integrated modelling of nitrate contamination of a large scale aquifer: Economical modelling and scenario development. *Paper presented at the International symposium Aquifers Systems Management, Dijon, France: 30 Mai-01 June, 2006.*

Graveline N. and Rinaudo J-D and Segger V. (2005). Simulating the economic impact of groundwater protection scenarios on the farming sector of the upper Rhine valley EU-project MoNit: Decision support system to assess the impact of actions and changing frameworks on the nitrate load in the upper Rhine valley aquifer. models and scenarios. *Paper presented at the EWRA conference, Menton: September 7-10, 2005.*

Work in progress

Graveline, N.. Economic calibrated agricultural supply models to inform water management and policy: a review (2013) *Working Paper*

Contents

List of acronyms

ANR: Agence nationale de la recherche

BAU : Business as usual

BRGM : Bureau de recherches géologiques et minières

CAP : Common Agricultural Policy

CES : Constant Elasticity of Substitution

DSP : Discrete Stochastic Programming

GAMS : Generic Algebraic Modeling System

GHG : Green House Gases GIS : Geographical Information System

GME : Generalized Maximum Entropy

INRA : Institut National de la Recherche Agronomique

IRSTEA : Institut ntional de recherche en sciences et technologies pour l'environnement et l'agriculture

IPCC : Intergovernmental Panel of Climate Change

IWCC: Intermediate Winter Covering Crop

LP : Linear Programming

LUBW : Landesanstalt fuer Umwelt, Messungen und Naturschutz Baden-Wuerttemberg

MoNit : Modélisation de la pollution des eaux souterraines par les nitrates dans la vallée du Rhin supérieur

MOTAD : Minimization Of Total Absolute Deviation

PHNR : Post-Harvest Nitrogen Residue

PM : Programming Models

PMP : Positive Mathematical Programming

PRA : Petite région agricole

RPG : Registre parcellaire graphique

SAGE : Schéma d'aménagement et de gestion des eaux

SRES : Special Report on Emissions Scenarios

WPM : Water Programming Models

WFD : Water Framework Directive

Chapter 1

Introduction - Synthesis chapter

1.1 Introduction

1.1.1 Background and purpose

In several parts of the world agriculture is responsible for a large share of surface and groundwater withdrawals (OECD, 2010) and for a significant part of the diffuse nitrate and pesticide contamination waters, while ensuring the raw food production of human societies. Changes in water needs and related pressures on water resources are likely to increase in the future because of various circumstances that are related to global change: the effects of climate change on water resource recharge and on crops' water needs, increases in population concentrated in favored areas such as coastal zones, and growing global demands for food and biofuel are among them (Vorosmarty et al., 2000; Sunding et al., 2002; European Environment Agency, 2010). Increasing demand for agricultural commodities implies higher prices, at least under some conditions, and this promotes an intensification in the use of agricultural inputs (land, fertilizers, pesticides, and water) so as to produce more. In return, these drivers have an impact on water resources and on the preservation of their good chemical and ecological status.

In light of these factors, efficient water management in agriculture is critical (Jury and Vaux, 2005). There is a clear need to predict how agricultural systems will respond to diminishing water availability, increases in input costs, and global change in order to limit both the externalities of agriculture on water and the costs supported by farming, while adapting to increased constraints. This should also help to evaluate water and agricultural policies and assist decision-makers in making informed decisions regarding water allocation.

Water regulations are an institutional response to the increase in environmental concerns. In the European Union, the Water Framework Directive (WFD) requires Member States to reach and maintain a so-called "good ecological status" for all bodies of water by 2015 or at the latest by 2027 in the case of exemptions (European Commission, 2000). This terminology covers both quantitative and qualitative criteria. The means for achieving this good ecological status are left to the evaluation of Member States, which are encouraged to use cost-effectiveness criteria in selecting an appropriate set of measures (European Commission, 2003; WATECO–CIS Working Group, 2003). This latter requirement necessitates the provision of methods for assessing alternative policies aimed at regulating water use and water management. For the first time the policy is targeted on reaching an objective rather than simply employing certain means.

The requirements of the WFD and of the ensuing equivalent national legislations imply that reductions in agricultural water withdrawals and significant efforts in developing farming practices to reduce diffuse pollutant loads should be focused on water catchments classified as being at risk of not achieving the good status. The cost to the farming sector and the potential structural damage to it are not considered, although a postponement of the deadline for achieving good status until 2027 may be obtained if the costs are shown to outweigh the resulting benefits.

In France, the national transposition of the Water Framework Directive is the *Loi sur l'Eau et les Milieux Aquatiques* and it includes, among other items, a revision of the withdrawals authorization, i.e., rights, in order to ensure a good quantitative state. This could have a significant impact on irrigated agriculture. Opposition to these new constraints on water users has led some studies to assess the costs for the farming sector as a whole (Hébert et al., 2012). Major reductions in water availability might indeed have important impacts; in some areas the agricultural sector could become too vulnerable and might halt certain productions, reducing local food supply, increasing prices, and causing jobs to be lost. For this reason methods are needed for assessing the economic costs by representing the choices facing agriculture, including all possible adaptations, in order to estimate the impacts on farming of water policies and global change.

1.1.2 Research issues

Trade-offs between water conservation and agricultural production development are obviously important. One of the main challenges justifying the present study is to simultaneously ensure both agricultural production and water conservation.

Three issues are at the core of this research:

The need for foresight and assessment of the impacts of global change

From a social planners' or decision support perspective, a primary concern when planning environmental policy is to assess the gap that exists between the current environmental state and the objective, while taking into account the future evolution of both economic and biophysical variables. A long time might pass before a regulatory measure becomes effective, in the case of a groundwater with a long transport or reaction time, for instance. In such cases considering both the change and the uncertainties in the variables of the hydro-economic problem is critical to correctly assess the marginal effects of measures on both water resources and on farming if we are to evaluate their desirability. Moreover, if the regulatory program is designed to target a 2003 deficit, and the Water Framework Directive requires a good state by 2015 (or 2027 at the latest), it is very likely that it will no longer be appropriate, given that the problem's variables will have evolved in the meantime. As already discussed, global change will affect a number of biophysical and economic drivers. Figure 1.1 illustrates the need to account for the changes in these drivers in order to design appropriate policies and to avoid making errors in the environmental target. The first research issue we address in this work is **to assess the level of pressures exerted by farming on water resources at some future time horizon (5 to 30 years) and their uncertainties**. This question is central to Chapter 3.

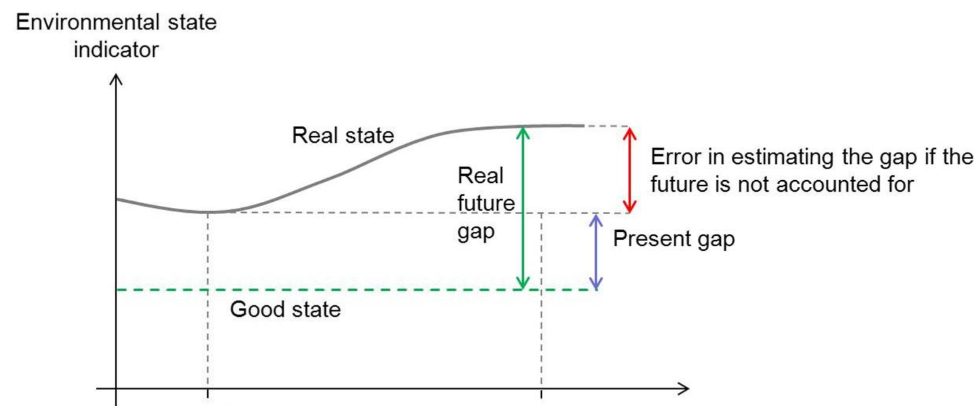


Figure 1.1: The need to account for future evolution in environmental policy

Assessing the level of non-compliance with WFD objectives for each and every body of groundwater is, however, not a trivial task, since the future evolution of contamination, e.g., nitrates in aquifers, and of their quantitative state, e.g., piezometric levels or flows depends on complex interrelated biophysical processes such as transfer, transport, and attenuation, and on economic processes such as emissions or withdrawals by the farming sector. Therefore assessing possible future changes in groundwater quantity and quality should be carried out by using integrated models capable of simulating the changes in pressures, e.g., pollution sources, pathways, and receptors. Coupling or integrating economic and biophysical models seems to be a relevant approach for simulating future changes in agriculture as regards cropping patterns and practices (input usage), since these are key factors determining groundwater quality and quantity. Such models may be referred to as hydro-economic models (Harou et al., 2009).

A related issue is how to account for uncertainties that may affect the whole system. Biophysical and economic uncertainty can be distinguished. Biophysical uncertainty concerns climate or pest attacks that will have an influence on yields and production, while economic uncertainty refers to price and policy uncertainty. Considering several scenarios instead of a single future scenario allows us to account for the uncertainty related to major changes in the drivers, i.e., an environmental orientation in agricultural policies, and the consequent effects. Foresight approaches, often referred to as "scenario planning" or "scenario analysis", e.g. Peterson et al. (2003); Duinker and Greig (2007); Reed et al. (2009), have been developed for this purpose. Uncertainty can also be studied by multiplying the number of simulations performed while varying certain parameters. We develop an approach in Chapter 4 that enables the coupling of a broad sensitivity analysis and a scenario analysis in order to explore the effects on various scenarios and how their uncertainty affects water resources and agricultural economics.

Water policy analysis

A second challenge is then to identify, design, and evaluate policies that encourage the reduction of pressures exerted by farming on water resources. In concrete terms this means the adoption of alternative management options or adaptations that can be achieved at minimal social cost. **One of the main questions we address in this work is the cost-effectiveness of various policies for reducing the pressures on water or water's externalities** water being an open-access resource. We will focus on the nitrate contamination problem and agricultural water withdrawal.

Essentially, there are two types of instruments that may be adopted by policy makers. The first type encompasses quantity-control instruments, such as norms or quota-based instruments that limit the emissions of certain production outputs, e.g., nitrate, or the use of inputs, e.g., nitrogen. The second type includes price-based instruments[1] such as taxes on outputs or inputs or, conversely, subsidies intended to encourage the adoption of good practices and technologies. These have an indirect effect on the use of inputs because they increase the cost to the producer or consumer. In other words, price-based instruments act as incentives to reduce input use or related practices. From a purely theoretical point of view these two types of instruments are equivalent (Weitzman, 1974).

[1] or economic instruments

However, information asymmetries, uncertainties about processes (contamination in the present case), and rationality among other factors undermine this equivalency. Weitzman (1974) discusses this economic issue in detail. This policy question is central to the majority of environmental problems characterized by the control of negative externalities or the provision of public goods. The cost-effectiveness of a policy will depend on the response of the farming sector to it.

Nitrogen use is assumed to have an effect on groundwater nitrate contamination. However, the regulation problem is not simple because the biophysical process intervening between the application of the fertilizer to the crop and the concentration of nitrates in the water makes the transfer function highly non-linear and dependent on an important number of biophysical parameters (soil, crop, and climate characteristics). The policy implication is that optimal regulation depends not only on the economic behavior of farming but also on biophysical processes that are uncertain, e.g., climate. This is why the simulation of future nitrate contamination is an interdisciplinary challenge that requires us to represent both economic behavior and biophysical processes.

The agricultural water use considered in this study is confined to irrigation water only.[2] The regulation problem is slightly simpler than for nitrate regulation because the water applied to crops is directly and linearly related to the water withdrawn from the environment, but the relationship between the water withdrawn and the ecological impact is non-linear. The ratio between the water that is usable by crops and the water withdrawn is often referred to as the irrigation efficiency (Perry et al., 2009). As a consequence, policy analysis does not necessarily require biophysical modeling (see Chapter 5 where we assess the impact of increasing the constraints on water withdrawal rights). In some cases however representing the whole system enables an assessment of the joint medium- to long-term evolution of both agriculture and water resources, as we will see in Chapter 6.

While the water resource representation might be simplified or ignored in some cases, the relationship between water application and agricultural production is non-linear and thus requires a detailed representation of the economic processes. We will discuss these production function issues and their incorporation into economic models in the Review Chapter (2) and in Chapter 5.

Understanding and representing farming behaviour with a focus on input use

[2] Agricultural water demand includes also drinking water for livestock animals and other uses such as cleaning.

The first two research issues lead us to a third one, which is at the core of this research: **the behavior of the farming sector in the face of changing constraints and a changing economic environment**. To assess the future level of pressures on water resources as well as the response of farming to water policies, it is critical to correctly represent the behavior of farming with respect to input use and production, in order to assess both the environmental and economic effects. In this research, we are thus particularly interested in the behavior of farmers in relation to input allocation in production activities. This question can be envisioned with the theory of production economics (Beattie et al., 1985), in which farming is considered as an activity that produces various commodities or intermediate inputs with various technologies that require inputs. Following micro-economic theory, the standard assumption of rationality and of maximization of utility will be adopted. In the context of agricultural farms, this assumption can be further simplified as the maximization of net revenues; we discuss this in the Review chapter.

We are mainly interested in the allocation of nitrogen and water and their related derived demands. This could have been extended to pesticides, which constitute a third agricultural production input that has an impact on water resources.

The question of uncertainty is also a significant one when dealing with farming behavior, because farmers make their input allocation decisions in an uncertain context. Economic or environmental uncertainty makes their production, i.e., their revenues uncertain. These uncertainties may be taken partially into consideration when farmers make their input allocation decisions, in other words they may value uncertainty differently. The risk-averse farmers whom we model in Chapters 3 and 4 value risk negatively.

The present work develops and discusses several types of models that are aimed at representing the behavior of farmers or farming in the context of global change and alternative water policies. We choose to develop programming models instead of econometric models for various reasons, among which is the ability to represent situations that have not been observed in the past. We also explore how economic models can be combined with biophysical models, i.e., agronomic and hydrogeologic models, or with data to assess the impact of both baseline scenarios and alternative policies. The models developed and discussed enable us to simulate the effects of reductions in inputs (of water or nitrogen) as well as the effects of combined policy scenarios and global change scenarios on farming economics and water resources.

1.1.3 Outline

This thesis comprises five main chapters, besides this summary chapter. The first chapter is a review that presents and discusses the literature on water use and the impact of agriculture within agricultural-supply modeling. Chapters two through five present four essays that address the impact of water policies and global change on farming and water resources. They build on various mathematical micro-economic programming models that, for the second and last, are connected with biophysical models designed to represent the impact - and the constraints - on water resources. The first essay (Chapter 3) discusses the evolution of farming and nitrogen-management practices in order to assess the evolution of nitrate contamination in the large Upper Rhine aquifer (France and Germany). The second essay (Chapter 4) deals with the effect of uncertainty on environmental and economic results, building on the case study in Chapter 3 and another in southwestern France by developing a refined Monte Carlo simulation approach. We suggest that this way of incorporating uncertainty is a means for mitigating the limits of linear programming. The third essay (Chapter 5) focuses on the adaptation of farming to water scarcity in the particular case of the Beauce aquifer (France) and its water-quota regulation scheme. We develop and discuss positive mathematical programming (PMP) models that enable the modeling of farming response to water scarcity at the regional scale, and improve calibration in comparison to linear programming, specifically by calibrating the yield response to water application. Three alternative calibration methods are detailed and we propose a breakdown of the responses of farmers to water reduction under three different adjustment margins. The last essay (Chapter 6) is an attempt to integrate economics and hydrogeology in a single model so as to identify some specific relationships between indicators in the economic model and the hydrogeological characteristics. We address the same question of farming's adaptation to water scarcity, but this "holistic" model also enables us to address the question of the efficiency of the whole regulation system using dynamic simulations, and thus to analyze alternative water policies in detail.

We conclude by discussing the suitability of the various modeling approaches for informing water policy and management on specific policy implications, and considering the further implications of the present work.

1.2 Modeling agricultural sector input use behavior and its impact on water resources

Models are widely employed in applied economics. They are a straightforward representation of reality and enable the analysis, simulation, and optimization of the allocation of scarce resources in various institutional settings. Their purposes are diverse and range from exploring optimized allocation to more pragmatic, ex-ante policy simulations.

One of the methodological challenges of this work is to adequately represent the behavior of farming or individual farmers with respect to input use. Input use can be expressed as a derived demand from the agricultural production process. In our case we are concerned with water use for irrigation and nitrogen use as fertilizer. Derived fertilizer and nitrogen demands are theoretically the same as water demand. However, the fertilizing issue in relation to environmental concerns has been less frequently treated from this viewpoint and more as an externality of farming. Water demand seems to have been more extensively studied than fertilizer demand.

Agricultural economics has developed various approaches to model the derived demand for the inputs of agricultural production. Since water for irrigation is one of the inputs, irrigation water demand can be assessed by micro-economic theory. There are a number of empirical economic methods available for assessing agricultural water demand: programming models, econometrics (Moore et al., 1994; Hendricks and Peterson, 2012) and field experiments (Bouarfa et al., 2011) are the most popular methods. Others include Data Envelopment Analysis (DEA, Frija et al. (2011)), hedonic pricing (Faux and Perry, 1999) and contingent valuation (Storm et al., 2011). Among empirical models the most popular approaches are econometrics and programming models, with a higher number of published programming models (Scheierling et al., 2006). They are detailed in Chapter 2.

Analytical models are also used on a theoretical basis but there has been no attempt to fit to observed data, i.e., the real allocation of resources. The aim is to analytically explore the problem and equilibrium; the problem's formalization is determined on the basis of theoretical assumptions. In these analytical models the central question is often the optimal control of temporal groundwater allocation of water from a planners' perspective.[3] Examples are

[3]They are often concerned with the so-called Gisser-Sanchez effect (GSE) that states that optimal control (i.e. temporal management) of the resource does not provide significant benefits over the non regulated, myopic, case (Gisser and Sãnchez, 1980).

Provencher and Burt (1994); Rubio and Casino (2001); Koundouri (2004b); Koundouri and Christou (2006).

Programming models of agricultural supply are based on production economics (Beattie et al., 1985) since the core of the model aims to reflect a production process characterized by a technology, its production functions, and the costs of inputs, and on product prices. They are in line with neo-classical theory because they make use of mathematical formalism and build upon methodological individualism, but they do not consider the consumer.[4] In supply models, the demand for agricultural products is assumed to be inelastic and is exogenously characterized. In addition, the producer is considered to be a price-taker. This implies that the area considered is small enough that the supplied production represents a small share of the commodity market and does not influence its price. Calibrated models are based on the economic assumptions that individuals, here the producers, have a rational behavior and maximize their utility, often simplified as the profit. However, alternatives such as multi-attribute utility theory (Keeney and Raiffa, 1993) can be implemented to better represent decision-making in certain cases, and to account for the fact that farmers are not only producers but also consumers. Applied to agricultural water use, supply modeling's overall goal is to infer the economic value of water associated with its use in agricultural production. One of the modeling issues will be to isolate the water quasi-rent from other inputs, mainly land and rent.

Econometric models are estimated on observed data and their advantage is to be very flexible in fitting the observed data, with little constraint on their functional form. This is a pure "positive" approach. Their interest is that they explain economic phenomena by identifying determinants (significant variables), sometimes with the objective of predicting the evolution of dependent variables. It may be very relevant in some water management issues, for instance it can provide an understanding of real irrigation-technology choices (Green et al., 1996). One of their main limits is that they may not be valid when simulating policies or parameter values, i.e., prices, that are out of the range of past parameters, since they represent only the behavior of past and previously observed, i.e., measured situations (Lichtenberg et al., 2010). This is a major drawback when modeling the evolution of production behavior in a global change context, where a particular future situation may not have been faced in the past, for example climate change, a particular variable, or high cereal prices. Another drawback of econometrics is that it often provides an overly high level of aggregation across differing small regions or farm types.

[4]Partial and general equilibrium models do.

One of the biggest advantages of calibrated models, over econometric models in particular, is that they incorporate explicit and crop-specific production functions that link agricultural production[5] with input use. This enables to link agricultural production and its impact on water resources directly, in the case of water for irrigation, or indirectly in the case of diffuse nitrate contamination. This is not the case with econometrics, which is a problem for the environmental and externality analysis of farming systems. Another important advantage, from our viewpoint of representing the impact of future evolution or policies, is that programming models are better suited than econometrics for simulating situations that have not yet been observed. Lastly, programming models can handle cases with relative small datasets in comparison to econometrics which requires large datasets. This is particularly the case when dealing with water use on crops in France, since few data have been systematically collected on this topic. Its principal shortcoming is that no systematic standard errors can be assessed using programming models, as opposed to econometrics. Programming models (PM) of agricultural supply have been used by several authors in the literature to simulate the impact of water scarcity, water quality, and water policies on agriculture (Dinar et al., 1991; Ribaudo et al., 1994; Maneta et al., 2009; Medellín-Azuara et al., 2010; Mérel et al., 2011; Graveline et al., 2012).

In light of this, mathematical programming to model agricultural supply appears to be the technique best suited for exploring the future evolution and impacts of water policies on the agricultural sector, and on the environment, in real-world settings. We will develop this point in the first chapter. The adaptation of agriculture to reduced input availability and to increases in their costs, as well as consideration of their externalities, are fairly new topics for the application of mathematical programming methods in the agricultural sector. Accordingly, the specification of models must be adapted for these new modeling issues. Indeed, the classical implementations of programming models were intended to simulate the ex-ante impacts of agricultural policies such as CAP reforms, and might have focused on representing the market effects on farms and the farming sector (see for instance Arfini et al. (2005); Boussard et al. (1997); Barkaoui and Butault (2000)).

While economic models are developed to represent the behavior of farming with respect to input use, biophysical models are required to represent the effects of input use or pressures on water resources. Connecting economic models with biophysical models such as soil and crop-growth models and hydro(geo)logical models may be referred to as integrated modeling

[5] in quantity and economic value

(Janssen and van Ittersum, 2007).[6] Hydro-economic model terminology refers to those models that incorporate, at minimum, an economic (user) model and a hydro(geo)logical model (see Harou et al. (2009)).

Empirical hydro-economic models are often concerned with the effects of alternative instruments on the hydro-economic system, e.g., Ward and Pulido-Velazquez (2007); Pena-Haro et al. (2010); Balali et al. (2011), or with the estimation of the economic value of water (Medellìn-Azuara et al., 2009; Pulido-Velazquez et al., 2008). The main distinction that can be made between them is the compartment versus holistic approach. Holistic modeling keeps both the economic and biophysical characterizations (equations) under a unique control program and equations are solved simultaneously, e.g. Cai et al. (2003); Rosegrant et al. (2000); Medellìn-Azuara et al. (2009). This enables a simultaneous solving of both hydrological and economic models with multiple feedbacks and relationships between the different variables. In these cases the models are often highly simplified. The other approach may be called the compartment or modular approach (see for example Lefkoff and Gorelick (1990); Graveline et al. (2013)) and has the advantage of also being suitable for distributed hydro-geological modeling, since each model has its own interface, adapted to its requirements.

1.3 Background and case studies

The overall context of our problem is the increase in water-related constraints for farming and the consequent adaptations and related costs. To discuss our research questions and illustrate the methodologies developed, we will base our work on two main real-life case studies for which we analyze specific policy implications.[7] Many different local characteristics are significant in evaluating the relevance and efficiency of water policies and the impact of trends in the economic and regulatory contexts. The first case considers agricultural nitrate contamination in the Upper Rhine aquifer in Alsace, France; the second focuses on the quantitative management of groundwater in the agriculture of Beauce, France.

[6] Bio-economic model terminology is used when there is no water resources compartment

[7] A third case study in Chapter 4 is the Neste system in southwest France. I did not develop the models for Neste, although my co-authors did which is why I have not presented it here

1.3.1 Regulatory background : the Water Framework Directive

Europe adopted an ambitious policy for the management of aquatic ecosystems and water resources with the promulgation of the Water Framework Directive (WFD). This directive prescribes results-driven goals, in terms of the overall good status of water resources, defined as a combination of good quantitative (or qualitative) and chemical status, aimed at ensuring a good ecological quality in aquatic environments (European Commission, 2000). It requires Member States to implement water monitoring and measurement programs to restore their aquatic environments to a good ecological status by 2015 or, in the case of an exemption, by 2027 at the latest. To achieve this, the WFD recommends implementing a two-stage procedure: the first stage consists of developing a business-as-usual scenario, against which the risk of failing to achieve good status can be assessed and the distance to the objective estimated. The second stage involves designing an action program for achieving the objective, through a reduction of pressures of human origin (Rinaudo and Strosser, 2007). For instance, nitrogen-abatement programs will be necessary for all water bodies characterized as being at risk of failing to achieve the good ecological status owing to nitrate contamination. This objective was clarified with the publication of the *daughter* groundwater directive (European Commission, 2006). The WFD risk assessment for France states that 39% of the 553 French groundwater bodies[8] are at risk of failing to achieve good status; 18% have not been classified because of doubts concerning the assessment or missing data, and 43% have been classified as being in good status. The main risk criteria employed in classifying groundwater bodies are nitrate and pesticide contaminations (Ministère de l'écologie et du développement durable, 2008).

The WFD particularly concerns agriculture, because farming exerts a significant pressure on water resources in terms of both quantity (water abstraction for irrigation) and quality (pollution by livestock effluents, mineral fertilizers, and phytosanitary substances). Agriculture is thus primarily responsible for the classification of water bodies as being at risk for nitrate or pesticide contamination, or having quantitative status problems.

[8]Water bodies are the units that have been defined as homogenous ground or surface water resources in the context of the WFD and the national transposed legislation

1.3.2 Nitrate contamination evolution and regulation in the Upper Rhine aquifer (Alsace and Baden)

The Upper Rhine valley aquifer is an interesting case for studying agricultural nitrate contamination: it covers more than 4,200 km^2 and is shared by Germany (Baden region) and France (Alsace region); a small area extends into Switzerland. With a reserve of approximately 45 billion m^3 of water, it is one of the largest freshwater resources in Europe. The water supply of more than three million inhabitants of the Alsace (France), Baden (Germany) and Basel (Switzerland) regions directly depend on this resource. Approximately 300 million m^3 are extracted every year for drinking water, 45% being used in France, 35% in Germany, and 20% in Switzerland. Groundwater also supplies 50% of their industrial water needs. Since the 1970s, the groundwater has increasingly been affected by diffuse nitrate and pesticide pollution, mainly due to the intensification of agriculture. Agriculture covers about 230,000 hectares of the aquifers' extent in France and Germany. The nitrate pollution problem is particularly acute on both sides of the Rhine. While the nitrate concentrations were lower than 50 mg/l throughout the aquifer in the early 1970s, 15% of the 1,100 monitored points had a nitrate concentration exceeding 50 mg/l in 1997 and the European guide value of 25 mg/l was exceeded in 36% of the monitored points (Région Alsace, 2000). Figure 1.2 shows the distribution of nitrate concentrations in the aquifer in 2000. Groundwater showed high nitrate concentrations in areas where intensive crops (corn or grapes) were cultivated (some corn is also cultivated by irrigation in the southern Hardt region).[9] The area farmed for corn and grapes has been increasing, whereas the area occupied by grassland has steadily declined. Between the two agricultural censuses (1988 and 2000), the area under vines has increased by 13%, and the area under corn by 60%, whereas areas under wheat and grassland decreased by 25% and 13% respectively. It is accepted that these changes are responsible for the groundwater contamination.

As a consequence, nitrate contamination together with pesticides has been assessed to be a major cause of non-compliance with the objectives of the Water Framework Directive (WFD) in the Upper Rhine valley aquifer (Ministère de l'écologie et du développement durable, 2008). Evidently the programs of measures implemented by European Member States to comply with the Nitrate Directive of 1991 (91/676/EEC) seem to have been insufficient to reverse the pollution trends and to achieve the targeted nitrate concentration of less than 50 mg/l in all the areas identified as vulnerable (European Commission, 2002).

[9]However, the quantative status of the groundwater is not endangered by excessive withdrawals regarding its natural regime.

The situation is not likely to change soon, given the high inertia of groundwater systems, possibly resulting in a large number of groundwater bodies not achieving the targeted 50 mg/l by 2015.

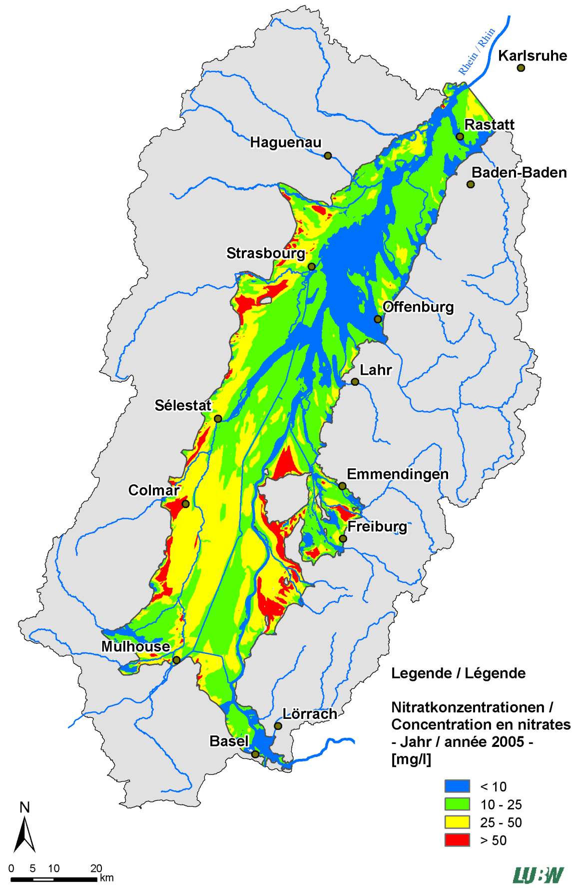


Figure 1.2: Distribution of nitrate concentration in the Upper Rhine valley aquifer in 2000. Source : LUBW, 2006

Nitrate contamination of groundwater causes significant economic damage at the regional level. It has lead to the closure of an increasing number of drinking-water wells, it contributes to the decline of consumer trust in tap water and a rise in bottled water consumption, and it creates technical and economic constraints for industry. In the Alsace region, the total cost due to nitrate contamination between 1988 and 2002 has been estimated to be at least € 196 million for drinking-water utilities, households (bottled water purchase, and the installation of filtering devices at home), and industry (nitrate-removal plant) (Rinaudo et al., 2005).

However, this trend is likely to be significantly altered in the future in response to changes in European agriculture and environmental policies, agricultural markets, energy prices, and the natural environment. To target the appropriate level of abatement it is necessary to consider these factors in order to assess the likely course of the environmental trend. This is the main objective of the work presented in Chapter 3.

1.3.3 Adaptation of irrigated farming to the reduction of water availability in Beauce

Our second major case study area is France's Beauce region. Beauce is Europe's main supplier of cereals (Eurostat, 2012) and also hosts one of the most irrigated agricultures in France (see Figure 1.3); it covers about 650,000 hectares. Since the 1970s, irrigation has developed substantially to cope with dry years, secure high yields, and enable the diversification of crop production. Currently, depending on the year, between 120,000 and 240,000 hectares are irrigated by pivot and hose-reel irrigation systems, withdrawing between 150 and 450 million cubic meters per year. This irrigation essentially relies on a large groundwater resource: the Beauce aquifer. It is a multi- layered aquifer with sands, chalk, and limestone that covers 9.700 km^2. The Beauce aquifer, once called the "château d'eau" (water tower) of France, is used for irrigation, drinking water, and industry. It also feeds natural surface-water systems, including the Loire river, thereby providing important ecosystem services (wetlands, biodiversity). This aquifer system faces quantitative problems, as evidenced by the lowering of the water table since the beginning of the 1990s and by reduce flows (drought) on connected surface rivers. One of the factors that may account for aquifers such as Beauce not being classified as at "quantitative" risk is that the management of these resources and the reduction of withdrawals to fit the natural capacity of the aquifer production were initiated before the formulation of the European Water Framework Directive and its implementation. Groundwater use in Beauce was first regulated only by temporary restrictions in summer, but since 1997 it has been regulated under an individual volume-based quota system at the farm level (Petit, 2009). Each year, a coefficient reflecting the state of the groundwater at the beginning of the cropping season is established by the administration. The reference quota is updated every year at the beginning of the campaign, according to this yearly coefficient (the coefficient is multiplied by the reference quota to determine the volume that can be pumped each year). For instance, in 2008, the yearly coefficient was 45%. Since 2009 individual coefficients have also been calculated for four hydrogeological units (sub-sectors of the Beauce aquifer) that display differing physical properties. The reference quota, i.e., when coefficients are 1, is 420 million cubic meters. There are no restrictions on the dynamic use of water, which means it may be used partially, or totally on spring or summer crops. Accordingly, farmers must plan both cropping and irrigation patterns jointly, at the beginning of the campaign and under uncertainty regarding spring and summer weather parameters.

Announcements of the yearly water availability coefficient are made in March or April. Throughout the year, a website informs farmers on changes in groundwater levels. Although the current management scheme has been recognized to be a step towards sustainable management, it has not been sufficient to suppress all water resource problems during the summer. Indeed, in the summer of 2011 crisis surface flows were reached in several parts of Beauce. Obviously this management scheme can only be transitory.

In this context, there is a clear need to understand how farming can adapt to water scarcity and to assess the costs to agriculture of reduced water availability. We will focus on long-term adaptations[10], i.e., adaptations that occur before cropping patterns are determined, as water scarcity is reflected through the coefficient applied to water quotas. This information is available to farmers before they decide upon their cropping patterns. Alternative policies also need to be envisioned, so as to allow further adaptation at the regional scale and to reduce the social costs of water scarcity. These include the strengthening of quota reductions in the eastern part of Beauce where the aquifer is more fragile, and the substitution of pond water (collected in wintertime in the eastern part of the area) for groundwater.

[10] as opposed to short-run (after cropping pattern planning) adaptations of farmers to water scarcity, see Reynaud (2009).

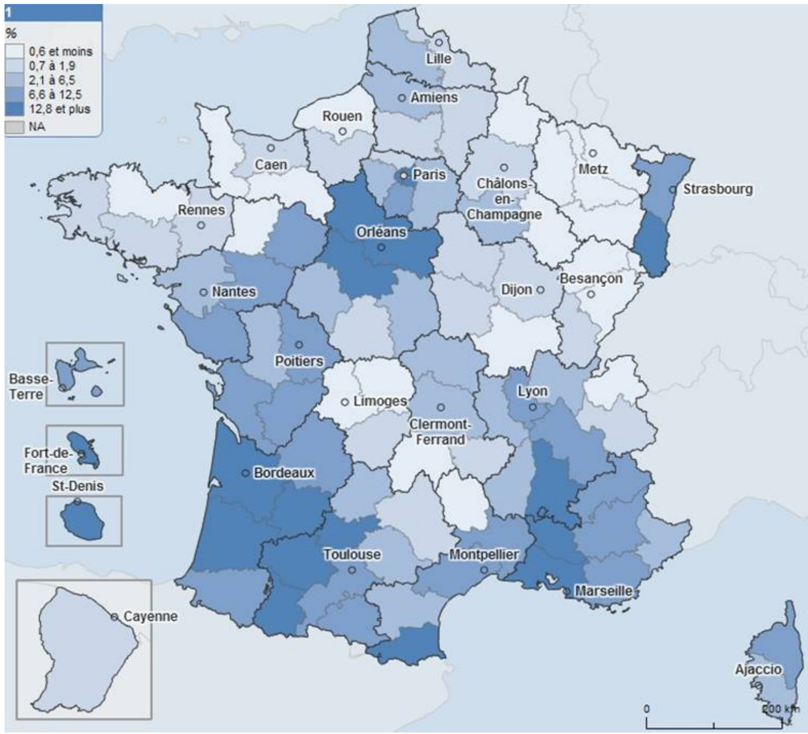


Figure 1.3: Percentage of irrigated areas in the usable farm areas in French *départements* in 2010 (Source: MAAF 2012-IGN GéoFla2010)

1.4 Economic model

1.4.1 General model form

The methodological challenge of this work is to represent the behaviour of farming with respect to water use and related constraints on nitrogen and water withdrawal. We choose to explore the interest of economic mathematical programming for the reasons explained in paragraph 1.2. The general form of the model is as follows: it maximizes utility under a number of resource constraints. As in the majority of supply models we assume utility maximization to be equivalent to profit maximization (we discuss this point in paragraph 2.3.1).

$$\max_{x_{ij}\geq 0} \Pi = \sum_i \left[p_i q_i - \sum_j C_{ij} \right] \quad \text{with} \quad \begin{cases} q_i = f(x_{ij}) \\ C_{ij} = x_{ij} c_{ij} \end{cases} \tag{1.1}$$

$$\text{subject to} \sum_i a_{ij} x_{ij} \leq b_j \ \ [\lambda_j]$$

where Π is the objective function representing the profit or expected profit in the case of risk considerations, i the agricultural commodity (crop or livestock), q_i the quantity produced as a function of input allocation x_{ij}, j standing for the inputs (land only for the Upper Rhine models, land and water, for the Beauce models)[11] p_i the price of commodity i, and C_{ij} the total cost of input j for growing commodity i. In the linear model c_{ij} is the variable accounting cost per unit input j; in the PMP model a PMP cost is added to the accounting cost and is determined by the calibration.[12] In the linear case, $q_i = x_i y_i$ with y_i the yield per unit of area when the only input considered is land and the remaining inputs are considered to be in fixed proportion with land. This particular case may be designated as a fixed proportion model. This principle is adopted for modeling the Upper Rhine farms in Chapters 3 and 4.

The quantities and the costs can also be specified as non-linear functions of inputs. This is the case with Positive Mathematical Programming models as formalized by Howitt (1995a). We develop this approach in Chapters 5 and 6 to account for heterogeneity in the modeled regions and also for decreasing marginal yields. This is particularly valuable for representing the effects of water on quantities: produced quantities are not linear with water or nitrogen applied. We address this issue in two different ways in our two case studies. In the Upper Rhine case, we multiply the number of activities to overcome the linear structure of the model and to account for varying levels of nitrogen and associated (non-proportional) yields. We assume that quantities are linear with land since the models are specified at farm level. In the Beauce case the quantities are expressed as Constant Elasticity of Substitution production functions with decreasing returns to scale, i.e., non-linear, and we develop a detailed methodology for calibrating the model on agronomic production function that link water and yields. We also assume that quantities produced are not linear with land, because of land heterogeneity at the regional scale in Beauce. These non-linear forms are also interesting for technical, i.e., calibration reasons, because they allow for perfect calibration as stated by the principles of Positive Mathematical Programming (Howitt, 1995a). We discuss this extensively in the Review Chapter (2).

[11] As we will see in Chapter 3 we do not consider fertilizer to be a separate input from land as it is assumed to be allocated in fixed proportion with land for a given activity

[12] Some PMP models specify non-linear costs

The objective function can also be adapted to risk-averse behavior by stating that farmers maximize their expected profit. The MOTAD model (minimization of total absolute deviation, (Hazell and Norton, 1986)) adds a standard-deviation (SD)-like term to the objective function and maintains the objective function's linearity. The SD-like term is multiplied by a risk-averse coefficient. The model is calibrated by adjusting a risk-aversion parameter while comparing the simulated with the observed cropping pattern. This coefficient can be interpreted as a pass-through coefficient of the farmer's valuation of the variance of gross revenues. The higher the risk aversion, the more the farmers place a negative value on the variation of gross revenues.[13] This model is chosen to represent the behavior of farm types in Chapters 3 and 4, in order to improve the calibration.[14] We discuss alternative models that incorporate risk in the Review Chapter (2).

1.4.2 Spatial scale

In theory, the model should be applied at the scale where the decisions are made. As such, it should be the farm scale if we accept the assumption that farmers decide upon their own resource allocation and cropping patterns. We assume this assumption to be valid in France: even though farmers are sometimes bound to the transformation industry by contracts or quotas (for sugar-beets, specialized crops such as certain vegetables, quality cereals etc.), they eventually decide on their own input allocations. Gòmez-Limón and Riesgo (2004); Bazzani (2005); Bartolini et al. (2007) have also selected the farm scale for modeling agricultural water demand. In Chapters 3 and 4 we represent the Upper Rhine farmers as typical farms and develop a model for each farm type, because we are concerned with farm-level analysis from a policy perspective and with the significant diversity of farm types (milk, vineyards, and cereal-oriented growers) and their specific nitrate impacts and nitrogen management. Because of data constraints, however, models are sometimes specified at the regional scale, aggregating all farmers into one large farm. This is possible when sufficient homogeneity among farm resources and technologies is observed. It usually enables the modeling of more areas than with a farm-typology approach that may select only some of the existing types. In Chapters 5 and 6 we assume that the Beauce farms' technology and resources are sufficiently homogenously distributed among farms to assume

[13] As argued by McCarl and Spreen (1997) the MOTAD model does not have a direct relationship to a theoretical utility function. As such an interpretation with the classic Arrow-Pratt coefficient of absolute risk aversion (r_a) is not possible; $r_a = -U(x)''/U(x)'$, with U being the utility. For a linear model, the case for MOTAD, we would have $U''(x) = 0$ and this means risk neutrality.

[14] Reducing the distance between the observed crop allocation and the reference situation modeled

that the regional model represents a good approximation of the sum of individual farm behaviors.

1.4.3 Time scale

The majority of models that focus on agricultural water and nitrogen management are static models and the time scale is the year which corresponds to a growing season. In other words the model assumes that the farmer decides upon the input allocation for a given agricultural year without considering the subsequent years, i.e., the farmer is *myopic* in the sense that he does not account for future years, even though there are certain constraints that "link" the decisions in one year to the next growing season. However, for the annual crops (cereals, oilseed, vegetables) employed in our case studies this is a minor problem, which can for instance be managed with rotational constraints in linear programming.[15]

Consideration of multiple time periods within one growing season may also become necessary in some settings where input allocation decisions, e.g., irrigation water application, can be revised when new information is received, e.g., weather data or changes in the seasonal water withdrawal regulations. Discrete Stochastic Programming is a useful approach in these cases (see Rae (1971b); Dono et al. (2013) and paragraph 2.5.3 in our review chapter). This is not relevant for the Upper Rhine setting, where the modeled decisions relate only to land allocation that cannot be revised during the growing season (the farmer cannot seed a new crop once the growing season has started under French climatic conditions). In the Beauce setting, where we also consider water input allocation, the water resource availability (in the form of yearly coefficients to be multiplied by the water quotas) is known to the farmers at the beginning of the growing season and does not change, even though piezometer levels could change in different ways in different years. However, water allocation could be revised during the growing season to adapt to weather conditions, for example if the weather turns out to be particularly wet, the farmer might apply less water than initially planned for an expected average year. Nevertheless, we are not concerned here with these types of intra-annual variations, but with the overall trend of water resource scarcity increase as reflected in the yearly coefficients. For this reason we do not consider multiple time periods in our economic models.

It may be necessary to consider multiple-year dynamics in certain situations. This can be the case when the interactions between farming and water resources are significant and one

[15]For perennial crops this is different and time should be considered, e.g. Connor et al. (2012)

would like to explore the evolution of the hydro-economic system over time. In the Beauce region, agricultural water use is constrained by the state of water resources so as to ensure sustainable critical piezometric levels over time. In this case considering a recursive problem in which different years are "linked" with each other to represent the effect of the regulation on both the economics of farming and on hydrogeological indicators is relevant when testing alternative instruments for regulation. However, in this case the farmers are still optimizing their yearly input allocation. This is the context we build on in the last essay (Chapter 6).

Another perspective for time integration that we do not address in this work is the inter-temporal optimization of resource use by a social planner. In this case, the modeling perspective is no longer the representation of the real behavior of farmers, but focuses on the optimal social *mining* scheme for water. These models are commonly the analytical models discussed in the introduction and encompass works from Burt (1964); Rubio and Casino (2001); Koundouri (2004b); Koundouri and Christou (2006).

1.5 Assessing the impact of farming on long-term nitrate contamination in the Upper Rhine aquifer

Chapter 3 presents the development of the economic model and its incorporation into a larger hydro-economic modeling platform, used to simulate the future development of nitrate pollution under various scenarios of economic and regulatory change. This work was carried out as part of the MONIT project (INTEREG III) conducted in the Upper Rhine Valley from 2004 to 2006. The project aimed to assess the baseline trend of nitrate concentration in the aquifer and the effectiveness of possible agricultural nitrogen-management measures through the development and application of an integrated modeling platform. This platform comprises a soil-plant model (simulation of nitrate transfer in the unsaturated zone), a nitrogen-balance model (simulating nitrogen infiltration into the aquifer), a hydrogeological model simulating water and nitrogen flows within the aquifer, and an economic model (simulating farmers' decisions in terms of crop choices). Chapter 3 focuses on the economic farming model and shows, with the aid of biophysical models, how it serves the modeling of nitrate contamination evolution. The rationale for having an economic model in such a modeling platform is that agricultural land use and practices will undergo significant change in the future owing to external drivers such as policies and commodity markets among others. The economic model seeks to model the behavior of farmers with regard to input allocation in the presence of these external drivers. The economic model and its scenarios were developed in a collaborative research effort by economists, policy makers, and stakeholders.

1.5.1 Methodology

The first stage involved drawing up a farm typology using farm-scale data collected from all the farms in the Alsace and Baden areas located on the aquifer. These typologies are designed to reflect the maximum heterogeneity both within and among the farm types (Köbrich et al., 2003). For the German portion a classification procedure was created (specification of criteria and threshold values), while an existing typology was used and adapted on the French side. Statistical farm data were then used to classify the 23,000 farms in the study area; the statistical analysis was performed by Government agricultural agencies on both sides of the Rhine[16], using separate data sources (the 2000 agricultural census in France, CAP data in Germany) and slightly different classification methods. We then estimated the *potential risk of nitrate leaching* for each farm type, which is defined as the sum, for all crops grown, of the product of crop acreage by a crop-specific nitrogen-leaching index.

Twelve farm types, representing respectively 84% and 69% of the usable agricultural area in Alsace and Baden respectively, were selected based on their contribution to the total potential risk of nitrate leaching. For each type, a real farm was selected and a model developed, based on information collected through representative farm interviews. The models incorporate constraints related to crop rotations, labor availability, production quotas (sugar-beet and milk), and manure storage and management for livestock-oriented farms. A corn nitrogen dependent production function was constructed using values provided by the results of agronomic field trials; this is used in the model to represent the yield and the residual nitrate content response to the nitrogen input. Three levels of inputs are defined in each case: agronomic optimum (maximum yield called corn 3) and two agronomic suboptimum levels (corn 2 and 1). A manure-management constraint following the Nitrate Directive is also incorporated by stating that each field may only receive a maximum of 170 kg/ha of nitrogen in manure. The MOTAD approach to linear programming (LP) was eventually implemented to improve the calibration of farm-type models as compared to standard lin-

[16] for reasons of data confidentiality. In France, the classification work was carried out by the Governments' Agriculture Department (DDAF) on the basis of classification criteria specified by the Chamber of Agriculture (Chambre d'Agriculture Régionale d'Alsace, 2003).

ear programming. As already discussed, the particularity of MOTAD is that it takes into account the risk related to the variation in gross revenues[17] in the objective function.

The model simulates crop choices, input consumption (fertilizer, labor, energy), and farm income for the different input parameter values (agricultural prices and subsidies, regulatory constraints, changes in the price of inputs such as energy, fertilizer, labor, minimum set-aside constraint, etc.) which we characterize for three different context scenarios.

An expert group was consulted to identify the major driving forces (or factors of change) likely to influence farm decisions over the medium term (2015). These factors of change were sorted according to the impact they might have on diffuse pollutions, their uncertainty, the time horizon corresponding to the likely change, and the ability of the farm models to simulate their impact. Expected variation trends were documented based on existing technical literature for a limited number of driving forces: the CAP reform, the risk of proliferation of the corn rootworm, fuel-price increase and environmental policies (water taxes and bio-fuel crop development programs). Three coherent combinations of change-factor assumptions were compiled to produce differing scenarios within the overall context: a business-as-usual scenario (BAU) and two more extreme scenarios, one having a more liberal orientation (A1) and one a more environmentally driven scenario (B2). They were partly inspired by the Intergovernmental Panel on Climate Change (IPCC) (2000) SRES scenarios. For each driving force, specific model parameters are involved, e.g., regulatory constraints, commodity price levels, subsidies etc.

The economic models are then used in simulations to represent the impact of each driving force individually upon each scenario. The farm-scale outputs are then extrapolated and aggregated at the small agricultural region level ("Petites Régions Agricoles" - PRA) according to the typology statistics (number of farm types per PRA) in order to supply the land-use results to the biophysical modeling chain.

In parallel, a policy experiment was performed by simulating the effect of a tax on both fertilizer use and on the post-harvest nitrogen residue for two farm types (large cereal-oriented farm and milk-production oriented farm, in France and Germany).

1.5.2 Main results

All the scenarios have a long-term positive impact on nitrate contamination compared to the reference nitrate concentration. This is largely due to the considerable inertia of the

[17] prices times quantities

groundwater system, which reflects the long-term (and already observed) trend of reduced nitrogen inputs in farming. It is also due to a common trend in all scenarios towards the decrease of corn acreage in France, corn being one of the crops with the strongest impact on nitrogen leaching.[18] Germany exhibits a slightly different pattern because corn's share is already lower in the reference situation (no monoculture). The B2 scenario, which is associated with an environmental orientation of policies (energy policies favoring the biofuel industry to reduce greenhouse gas emissions, and water fees) turns out to be the worst in terms of groundwater nitrate contamination. The A1 scenario induces a very close, thus worst situation than the BAU scenario which shows less nitrate contamination level among all scenarios.

The three scenarios (BAU, A1 and B2) have significantly different impacts on cropping patterns and practices, which result in different levels of nitrate contamination in the aquifer. In the baseline scenario, the area under corn decreases throughout the study zone (-24% of the total agricultural land) to the benefit of cereals (wheat and a small proportion of barley) and, in a limited way, to rape which is transformed into biofuel on the farm. Corn monoculture is no longer practiced and two to three-year rotations become more frequent (corn/wheat/rape), mainly in France, and are generalized in scenario B2 as can be seen on Figure 1.4. In the A1, "liberal" scenario, cropping patterns are very similar to those of the BAU in Alsace, and, in Baden they show an increase in corn areas at the expense of cereals.

The differences between scenarios show that there is a certain level of uncertainty associated with future nitrate contamination. This demonstrates the need to include economic approaches such as the one presented here for medium- and long-term assessment of groundwater quality. However, the impact of surface activities (cropping patterns and nitrogen-related practices) on groundwater is delayed in time by the great inertia of the groundwater system. This result highlights the necessity of integrating detailed hydrogeological and soil models.

The fertilizing practices evolve differently depending on the scenario: the B2 scenario shows a higher adoption of low-fertilizing corn; however, this is not enough to counterbalance other "crop" effects. As we have seen, it turns out to be the worst in terms of nitrates. This is largely explained by the increase in the acreage of rape, which is associated with a high level of nitrogen residue and consequent nitrate leaching.

[18] one of the reasons is simply the higher application dose for this crop compared to wheat or barley and the subsequent increased risk of nitrogen leaching when major rains occur after fertilization

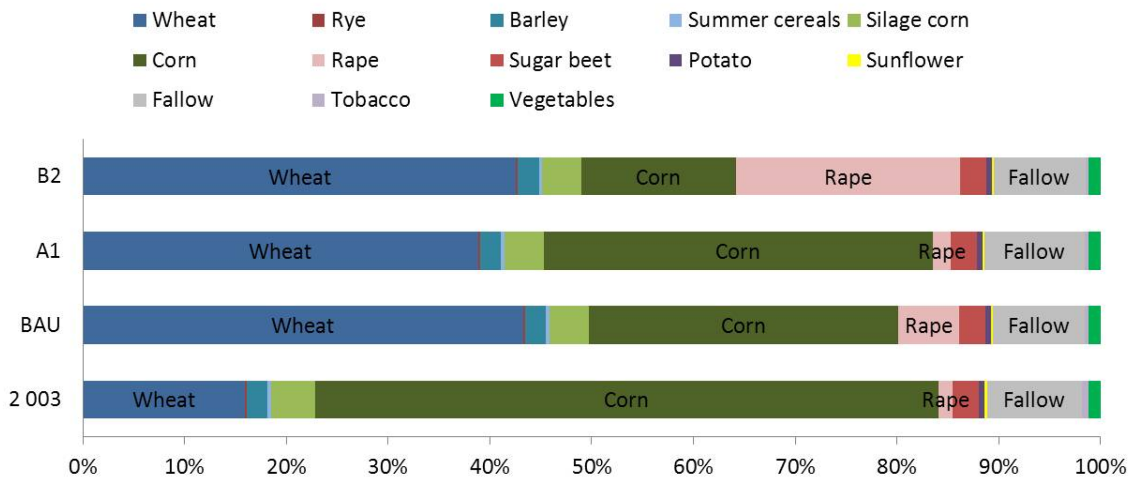


Figure 1.4: Distribution of total cultivated area per crop simulated with economic models - Alsace

The overall impact on profits and the value of total production are significant: for the whole area, the decrease in net revenue is 14% with a decrease of 9% in total production value for the BAU scenario. The B2 scenario in Alsace and the BAU and A1 in Baden show reductions of more than 15% of the value of total production.

The results also show that the 2003 CAP reform is not likely to result in a significant reduction of the potential diffuse nitrate pollution by farming. These impacts seem also to differ in Alsace (France) and Baden (Germany), because of differences both in the farms themselves and in the implementation of CAP reform: total decoupling in Germany, while France retains 25% of coupled crop subsidies. In France, almost no changes in cropping patterns are observed apart from the elimination of all tobacco areas and a reduction of 8% in water withdrawals. Decreases in revenues are greater in Baden (about 10%) than in France.

The policy exercise on taxes on fertilizer use and residue shows that the tax must reach a high level to be effective (i.e. induce changes in practices) and compared to the cost of nitrogen: €0.58/kg: €1.5/kg for the fertilizer tax and €3/kg residue for the residue tax for French C1 farms. However, the effects vary according to the type of farm.

1.6 Impact of farming on water resources: assessing uncertainty with Monte Carlo simulations in a global change context

1.6.1 Context of the problem and questions for research

As discussed before, assessment of the future state of water resources is a prerequisite for the correct targeting of abatement efforts. We also showed that nitrate contamination in groundwater is affected by the evolution of agricultural land-use as well as by water policies. This throws light on the impact of uncertainty in the overall context on groundwater state. One of the main difficulties inherent in constructing scenarios of agricultural development and the pressures it generates on water resources is how to handle uncertainty: pressures on water resources (water abstraction and diffuse pollution) are highly dependent on the crops and farming practices chosen, which in turn depend on the economic context and on the environment, e.g., water resource availability. The overall economic and policy context may change, especially as regards the prices for agricultural products (Persillet, 2009), public policies and related subsidies or taxes (Common Agricultural Policy reforms), prices for essential inputs such as energy, and climatic conditions.

Most of the hydro-economic models used to assess the environmental impact of agricultural policies are deterministic. The issue of taking uncertainty into account in environmental impact assessment studies emerged in the 1980s, but is rarely included in methodologies (Payraudeau et al., 2005). A first approach to dealing with uncertainty is to simulate the impact of a limited number of contrasted scenarios for change on the economic environment, i.e., the approach of Chapter 3. Another very common approach is sensitivity analysis.

For example, Gibbons et al. (2006) developed a methodology aimed at modeling the biophysical uncertainty associated with greenhouse-gas emissions at the farm level. The present work aims at developing and applying a method that combines the scenario approach with Monte Carlo simulations, which allows us to explore the impact of economic uncertainty on agriculture and its environmental pressure on water by using linear programming models.

Chapter 4 describes the development of this method via two concrete examples of the economic modeling of agriculture in two different French case studies: diffuse groundwater pollution through nitrate leaching for the Alsace case (the Chapter 3 French case study), and water abstraction, i.e., quantity issues for the Neste river system in the Midi-Pyrénées region of southwest France. The irrigated Neste system in the Midi-Pyrénées region is a river system which is replenished from dam water. In this area one third of the farms (3,360 in 2003) irrigate a total of 80,000 ha including 68% of corn, followed by soybeans and pulses; vegetables and fruit cover less than 1% of the irrigated area.

1.6.2 Methodology

The overall principle of the method is the use of farm-scale LP models to assess the impact on agricultural land-use and practices of uncertainty in the input parameters that reflect the evolution of the regulatory, economic, and environmental context. The rationale is as follows: in the medium term (in 2003 with a 2015 horizon) the product and input prices, water availability, and water requirements by crops are largely uncertain. However, we assume that in 2015 the farmer will have more confidence (less uncertainty) then we have in 2003 on the value of the 2015 harvests, and as such the uncertainty incorporated in the model (to characterize the behavior) is less than the uncertainty that characterizes the context scenarios.[19]

In the Neste case study, uncertainty was assumed to be significant for product and input prices as well as for water availability and the water requirements for crops. We chose not to associate any uncertainty with post-harvest nitrogen residues, i.e., nitrate leaching, because we were concerned only with the impact of economic uncertainty. To this end, we implement Monte-Carlo simulations. The Monte Carlo approach relies on generating a large number of very different alternative scenarios,[20] by allowing extreme but realistic model input parameter values to be randomly selected in determined intervals, as recommended by Mahmoud et al. (2009). The uncertainty of some parameters is specified to be a function of the uncertainty of other parameters, so as to increase the internal consistency of the scenarios and reflect the correlation between certain variables. These should reflect cause-and-effect relationships.

Specifically, we operate as follows. The uncertain parameters characterized in each of the context scenarios are considered to be stochastic variables. A distinction is made between Rank 1 stochastic variables and Rank 2 variables, which are dependent on a Rank 1 vari-

[19] This explains why we do not simulate a unique decision/behavior in the context of very large uncertainty. In the case of perennials - fruit trees, olives, vines etc.- this would have been different, since plantations last for decades and related decisions have to anticipate the future uncertainty

[20] In our case study we repeated 200 draws for each scenario. This represent 3600 simulations for the Alsatian case study (200 * 3 scenarios * 6 farm types). The Gaussian curvature method would have increased the robustness of the simulation since it allows the numbers of draws to be reduced while ensuring maximum diversity among the draws

able. The Rank 1 random variables considered are oil prices and wheat, rapeseed, and milk prices. We assumed that they are independent and obey a principle of uniform distribution between two boundaries. A random selection was made between the minimum and maximum boundaries of these Rank 1 variables. We then made a random selection of Rank 2 variables, which also obey a uniform distribution principle, according to the Rank 1 variables selected: price variations for the Rank 2 variables are proportional to price variations for the Rank 1 variables, assuming that this correlation is random, but within a defined interval.

Three scenarios: *business-as-usual (BAU), liberal and interventionist*, broadly inspired by those developed in Chapter 3, were characterized at the 2015 horizon. They combine economic and policy characteristics on the one hand, and climate characteristics on the other. These are used to simulate the impacts of a scenario on water abstraction for eleven types of farms in Neste[21] and on nitrate leaching into groundwater for six types of farms in Alsace.[22]

1.6.3 Main results

The simulations of the three scenarios on both case studies produced a large number of results. These results are no longer in the form of a single value, as in the deterministic case, but may be represented by a probability density function (for continuous output variables) or by frequencies (for discrete output variables). We discuss the variability of results within a type (C1) and the confidence of the environmental indicator (the Post Harvest Nitrogen Residue - PHNR) and compare results from this stochastic approach with its deterministic equivalent. Specific results are presented in Chapter 4, paragraph 4.3.

The 200 simulations for a given scenario and farm type do not systematically produce different cropping patterns, but a limited number of solutions. For example, there are 14 different solutions to the linear problem, i.e., 14 cropping patterns, in the 200 simulations made for type C1 in the liberal scenario. They are reported on Figure 1.5. The values of nitrate residues obtained for these cropping patterns are different but fairly close together (29 kgN/ha with a range of -3 to +9%). The range of variation is small, which is consistent with the relatively stable cropping patterns shown on Figure 1.5 (85% of the cropping patterns are the same if we consider only the type of crop, without considering either the type of wheat or the intensity of fertilization).

[21] Note that I did not do the model development of these models, Sébastien Loubier and Guy Gleyses from Cemagref did

[22] Those that were presented in Chapter 3

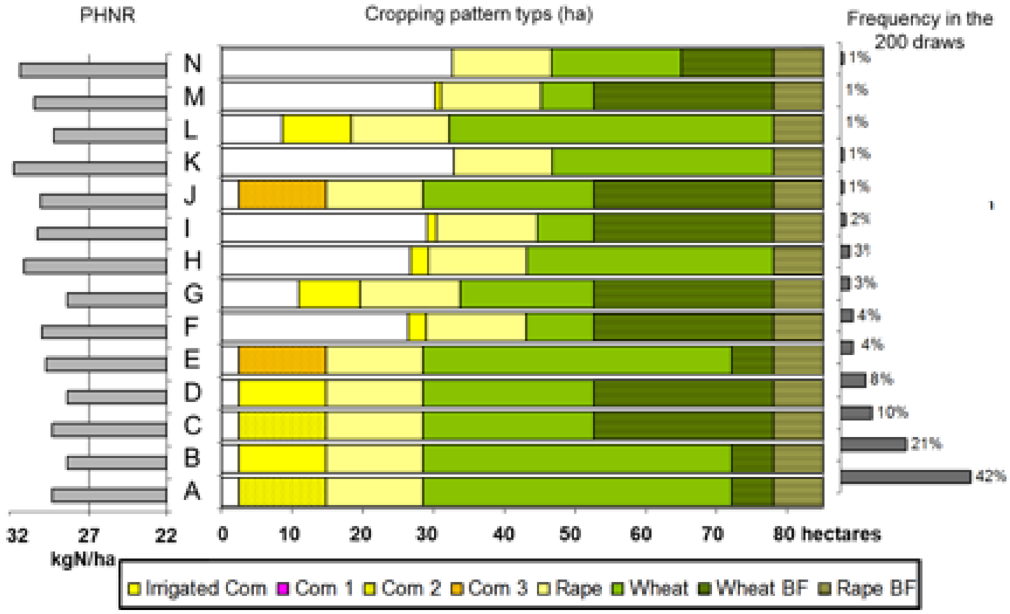


Figure 1.5: Cropping areas and their frequencies in Type C1 - Alsace - produced by the 200 simulations for the liberal scenario (in %) (white = fallow)

In all three scenarios, there is a significant drop of about 30% in PHNR, with variations within [-28% ,-43%]. Variations at the farm scale are also small despite wide variations in the initial economic context (see Figure 1.5). This is consistent with the results obtained in Chapter 3. However, residues are not evenly distributed around the mean. An interpretation of these means suggests that the liberal scenario produces less pollution than the interventionist one - although in some cases the interventionist scenario can lead to regional cropping patterns that produce less pollution than the least polluting patterns in the liberal scenario. Overall we may conclude that the uncertainty is not very significant from the water-planning and management viewpoint. A policy implication is that water policies can target a well-defined objective, and this reduces the risk of the policy failing. However, the uncertainty on income is greater. The uncertainty on cropping pattern is also greater, and identification of the most likely cropping pattern in the near-term future can help policy-makers to improve the design of agro-environmental measures that might be promoted for water protection, so as to ensure compatibility between encouraged practices and real cropping patterns.

A comparison between the Monte Carlo results and their deterministic equivalent[23] shows that the averages in all the Monte Carlo scenarios differ from those in the deterministic scenarios even if the differences are small (3 to 6% differences). This is explained by the fact that a deterministic scenario illustrates a specific case which has no reason to correspond to the average situation calculated from selections made within an interval of a discontinuous function. In other words there is no symmetry of responses in the Monte Carlo simulation around the deterministic value, because of non-continuity in the LP responses. Moreover, the results on profits and nitrogen residue are always higher in the deterministic simulations than in the Monte Carlo simulations.

1.7 Intensive and extensive margin adjustments to water scarcity in France's cereal belt

1.7.1 Problem setting

In Chapters 5 and 6 we adopt a different viewpoint than modeling the impact of global change on farming, and focus instead on the behavior of farming in response to a specific change: an increase in water scarcity and related increases in resource constraints or costs. The increase in water scarcity may result from a situation in which the natural capacity of water resources decreases[24] or where regulations become more constraining (policy).[25]

Farmers may respond on three principal margins to increasing water scarcity: (i) the super-extensive margin, that is, substituting irrigated crops for rain-fed crops; (ii) the extensive margin, that is, substituting water-intensive crops for less water-intensive crops within the set of irrigated crops; and (iii) the intensive margin, that is, the reduction of irrigation intensity on existing crops, also known as deficit irrigation.[26] Models aimed at accurately representing the impact of water scarcity and related policies on agriculture should ideally capture all three adjustments margins, each of which represents opportunities for the farming system to absorb shocks. Ignoring any one relevant margin will lead to overestimation

[23] The deterministic scenarios (BAU, Liberal and Interventionist) are defined with a unique set of input parameters that correspond to the central value of the intervals. See Table 4.1 in Chapter 4.

[24] reduction of piezometric level or in the natural flow of a river

[25] reduction of withdrawal quotas or authorizations or increases in the water fees recovered by basin authorities

[26] Another important margin consists of improving irrigation efficiency to increase water productivity through reductions in water losses due to leaching, runoff, and evaporation. We do not account for this because we assume that losses are negligible in Beauce where water is withdrawn by every farmer through wells and irrigation, using sprinkler technology.

of the economic impact of reduced resource availability and will bias cost-effectiveness measures for available policy options, potentially leading to poor decision-making (Frisvold and Konyar, 2012). Inferences regarding output effects may also be affected.

In order to represent the behavior of farming in response to an increase in water scarcity we develop economic farm programming at the regional scale. We apply our model to study the effects of water scarcity on agriculture in the Beauce region. Our case study covers 563,000 agricultural hectares and nineteen annual crops, eight of which are irrigated with groundwater from Beauces' aquifer. Groundwater withdrawals are regulated by a quota system in which quotas are revised every year according to the level of the aquifer.

1.7.2 Methodology

We develop a calibrated agro-economic model to represent the behavior of farming in response to water scarcity which takes into account the intensive, extensive and super-extensive margins by specifying water as a separate input from land. The model is calibrated following the principles of positive mathematical programming (PMP) methodology (Howitt, 1995a), as recently refined by Mérel et al. (2011).

Several factors justify the choice of PMP methodology. The main one is that these models are non-linear and allow for the representation of both the agronomic response of yields to water, and the heterogeneity of farm resources and technologies among the modeled regions. The non-linearity also allows for perfect calibration. We discuss this matter in detail in Chapters 2 and 5. Note that the choice to represent cropping decisions at the regional scale, rather than at the individual farm type level, is driven by three main factors. First, it enables us to use good-quality, high-confidence data systematically produced at the administrative department level by the Ministry of Agriculture, notably on crop yields. Second, it allows us to represent a very large proportion (more than 90%) of the cultivated area, which would have been difficult with a typology of farms, i.e., the method employed in the first two essays. Finally, it makes the best possible use of the information available on crop-yield responses to water by soil type. This is essential, since our purpose is to accurately represent intensive and extensive margin adjustments to water scarcity. Model parameters are calibrated so that the model exactly replicates an observed reference allocation of inputs (land, water) among activities (irrigated and non-irrigated crops), as well as an exogenous set of supply elasticities. A novel feature of our model is that it is also calibrated so as to replicate a set of agronomically-derived crop-yield responses to water, creating a sound basis for inference concerning intensive-margin adjustments, as suggested by Mérel et al. (2013). The non-linearity in our PMP objective arises from decreasing returns to scale at the crop level, rather than increasing marginal costs - as is often assumed in existing PMP models (Cortignani and Severini, 2009; Frisvold and Konyar, 2012). To investigate the robustness of our inference to the available economic information used for calibration, the returns-to-scale parameters are calibrated using three alternative calibration rules which each employ different data types. First, following recent trends in the PMP literature (Mérel and Bucaram, 2010; Mérel et al., 2011), we use exogenous supply elasticities. Such a calibration rule ensures realistic responses to price changes. The second calibration exactly replicates observed and accounting profits: this is convenient for analyzing changes in profits and may be referred to as "profit calibration". The last rule, which we call the GME rule, is an intermediate calibration that calibrates parameters in a generalized maximum-entropy framework so as to partially satisfy both of the first and second calibration rules.

The Beauce region is broken down into four hydrogeological zones, such that each region is assumed to be independent in terms of water use. These four zones correspond to the regulatory zones characterized by different water-withdrawal coefficients. The reference allocation that we replicate is a vector $(\bar{q}_i, \bar{x}_{i1}, \bar{x}_{i2}, \bar{\eta}_i, \bar{y}_{iW}, \bar{\lambda_1}, \bar{\lambda_2})$ of activity outputs $(\bar{q}_i)$, acreages $(\bar{x}_{i1})$, water uses $(\bar{x}_{i2})$, own-price supply elasticities $(\bar{\eta}_i)$, yield response elasticities to water $(\bar{y}_{iW})$ and rents for scarce resources, of land and water $(\bar{\lambda_1}, \bar{\lambda_2})$. In each hydrogeological region, the objective function of the programming model is as follows and observes constant-elasticity-of-substitution (CES) between land and water for irrigated crops (the regional index is omitted for notational simplicity):

$$\max_{\substack{x_{i1}\geq 0\\ x_{i2}\geq 0}} \sum_i \left[p_i \alpha_i \left(\sum_{l=1}^{2} \beta_{il} x_{il}^{\frac{\sigma_i - 1}{\sigma_i}} \right)^{\left(\frac{\sigma_i}{\sigma_i - 1}\right)\delta_i} - \sum_{l=1}^{2} (c_{il} + \mu_{il}) x_{il} \right] \quad \text{subject to} \quad \begin{cases} \sum_i x_{i1} \leq b_1 \, [\lambda_1] \\ \sum_i x_{i2} \leq b_2 \, [\lambda_2] \end{cases}$$

where p_i are output prices, c_{i1} are variable costs per hectare (excluding irrigation), c_{i2} are water costs (for irrigated crops), b_1 and b_2 represent regional resource availabilities and $\sigma_i > 0$ the substitution elasticities between land and water. The model parameters to be calibrated are the PMP adjusment costs μ_{i1} and μ_{i2} that enable replication of the observed cropping pattern in the reference allocation.[27] The technology parameters $\alpha_i > 0$, $\beta_{il} > 0$ for $l = 1, 2$ and $\delta_i \in (0, 1)$ are also calibrated. The substitution elasticities $\sigma_i > 0$ are set exogenously and we conduct sensitivity analysis on their values. The program is written in GAMS.

Data come from various sources: the observed cropping pattern that characterizes the reference situation is obtained by a GIS treatment that combines the RPG (*Registre Parcellaire Graphique*) data base and hydrogeological units in order to aggregate cropping patterns at the hydrogeological unit level that we have adopted for modeling.

1.7.3 Main results

The calibrated model is used to investigate two types of alternative water policy scenarios. The first is a reduction in water availability, i.e., withdrawal quotas of -10% to -30%. The second includes the possibility of transferring water rights between regions. Water transfers among regions represent a potential mitigation strategy for water scarcity, since allowing water to flow from low-value regions towards high-value regions improves the overall economic performance of agriculture.

Interestingly, we find that even for a small value of substitution elasticities (0.15), the contribution of the intensive-margin adjustments to the overall reduction in water use at the regional level is non-trivial and amounts to about 17-18% of the total effect. Intuitively, the reduction in irrigation intensity should be stronger for irrigated crops whose yields are less responsive to water stress, e.g., wheat and barley, as indicated by the agronomic yield-response curves used in the calibration phase. This is consistent with findings by Bouarfa et al. (2011) obtained with a participative approach to water-scarcity impact assessment; these authors suggest that irrigation on high-value crops and corn will be maintained, while cereals show deficit irrigation. The two extensive margins correspond to the larger share of water reduction: the super-extensive margin represents 56-59% of the total response, while the extensive margin accounts for 24-27%. Crop-level analysis reveals more subtle adaptation patterns. The sensitivity analysis shows a positive correlation between the elasticity of substitution value and the intensive-margin adjustment, which is consistent with intuition, as can be observed on Figure 1.6.

[27] These adjustment costs may be interpreted as non-accounting implied costs or benefits. One idea might be to interpret implied benefits as old coupled payments, i.e., farmers would associate a benefit with growing crops that were more subsidized because of their habits, or because they might think that these advantages could reappear in the future

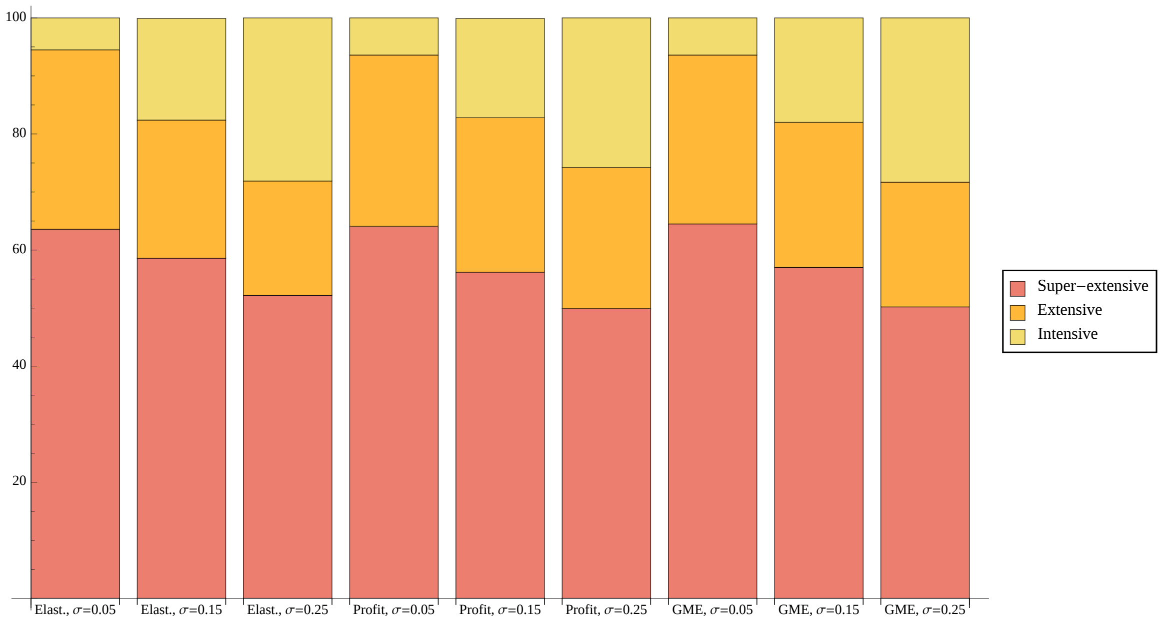


Figure 1.6: Relative importance of adjustment margins for a 30% reduction in water availability, according to the elasticity of substitution and the calibration rule

Cropping patterns show a similar pattern across sub-regions. Irrigated corn is the more responsive crop and its area drops by 42% for a -30% reduction in water availability (see Table 5.2). Irrigated sugar-beet, pulses, and durum wheat decrease by more than 10%. Wheat is less affected and major rain-fed crop areas increase.

Profits are only slightly affected by the water availability reduction scenarios tested: for -30% water availability, profits are reduced by about -1.10%. This finding is attributable to the modest share of irrigated agriculture (around 23% of the cropped area in the reference situation), the relatively large number of irrigated crops, and the possibility of deficit irrigation without much loss of yield on certain crops. These factors are directly related to the three adjustment margins discussed above. However, this large potential for adaptation involves a big predicted drop in corn output, which could affect downstream industry.

The model simulates significant water transfers from regions with relatively low shadow values towards regions with higher shadow values, as regions in Beauce show very different shadow values of water in the reference situation. Additional water in "receiving regions" is used to increase irrigation rates from 1% to 9% above the reference rates and to support an expansion in the acreage of irrigated agriculture by about 30%. However, these transfers offset only 6% of the economic losses due to water availability reduction, and the average benefit of transfers is estimated to be between 3-4 cents per cubic meter transferred. These results should be considered together with hydrogeological information to assess the desirability of a more flexible water-quota scheme among the regions.

1.8 Trade-offs between irrigated agriculture and groundwater management for alternative water policies in Beauce (France)

1.8.1 Context of problem and research issues

Evaluating alternative water policies for controlling the extraction of irrigation water from sensitive groundwater systems is a major challenge, both from an environmental viewpoint (Water Framework Directive or Water Law in France) and from an economic one. The goal is to ensure the sustainability of the dependent agricultural systems. To assess the overall cost-effectiveness of alternative water policies, there is a need to represent the combined effect of agricultural water withdrawal on water resources and the effect of reduced water availability on farming, and the dynamic interactions between the two phenomena. Modeling the hydrogeologic system together with the economic and regulatory system is referred to as hydro-economic modeling (Harou et al., 2009).

Hydro-economic modeling to address real-world policy issues is often developed in several different models (i.e. compartment approach[28]) as illustrated for instance in Chapter 3 or in Lefkoff and Gorelick (1990); Graveline et al. (2013), but we suggest that holistic ("all in one") hydro-economic models, e.g., Cai et al. (2003); Rosegrant et al. (2000); Medellìn-Azuara et al. (2009) have significant advantages over the compartment approach. These include allowing direct interactions between economic and hydrogeologic factors through the possibility of formalizing their processes jointly, and facilitating the exchange of input and output data between economic and biophysical processes. This enables optimization, multiple year simulation, and rapid simulation. This is also an advantage when working with decision-makers, because simulations are more easily implementable. These models rarely include the calibrated economic and hydrogeologic models (Cai and Wang, 2006) which we suggest here, and this is one of the methodological challenges in this final essay.

[28] where the models are expressed in several different types of software

To the best of our knowledge this is the first attempt to represent, in a single calibrated model, both a groundwater resource and irrigated farming behavior in France.

In the last chapter (6), we continue to focus on the Beauce case, as an illustration of a hydro-economic system characterized by irrigated farming which relies on a heterogenous aquifer for a water resource. The access to water is individual, via wells, and withdrawals are regulated by the administration on a quota basis. Agriculture takes most of the water from the Beauce aquifer, with a considerable inter-annual variability.[29] The quotas are revised annually according to the state of the groundwater resources, which in turn reflects withdrawals by users. The regulation is likely to change in the near-term, because of the changes in local groundwater governance (SAGE[30] and *"organisme unique"* implementation) and alternative policies are being envisioned. This essay develops a hydro-economic model in order to simulate medium-term changes (up to 2040) in agricultural economics and aquifer state, in order to evaluate alternative policies: a case with no regulation (open access), taxes and water withdrawal rights indexed on the water table, transfers to illustrate the opportunity of a market and substitution options. Climatic variability and change are also accounted for.

1.8.2 Methodology

We develop a holistic groundwater-economic agriculture model. It is a dynamic recursive model in the sense that optimization of the economic maximization function is carried out on a yearly basis (n), but it employs water-availability constraints that depend on year $n-1$ variables (withdrawals and climatic variables). As such, it corresponds to a multi-period simulation without inter-temporal optimization. Three main dynamic connections between the economic and hydrogeological models are represented in our model: (i) the withdrawal of water for irrigation is a parameter of the function of the piezometric head of the aquifer, (ii) the yearly regulatory constraints are a function of the piezometric head level, and (iii) the cost of water to farmers is a function of the depth of the aquifer. This last link can be considered to be an internalized externality: the more the farmers pump, the lower the piezometric level falls, and the more costly water provision becomes.

The economic model is very similar to those developed in Chapter 5; the profit calibration rule alternative is chosen because the hydro-economic model is developed in a policy

[29] Drinking water and industrial demands are less variable, because less responsive to variable weather conditions

[30] groundwater basin management plan

perspective and the decision-makers might be concerned with the profit.[31] The model is adapted to account for the variation in piezometric level in the energy cost of water pumping: as such the cost of water no longer has a fixed value per cubic meter water withdrawn and the piezometric level is internalized in the economic model.

Formulation of the hydrogeological model involved three main steps. The first aimed at defining homogenous hydrogeological zones, the second focused on gathering the data and calculating some of the model parameters, and the third step concentrated on refinement and calibration of the model. The Beauce region was broken down into six homogenous hydrogeological zones[32], such that each region is assumed to be independent in terms of water use. The time step is the calendar year and corresponds to current policy-setting requirements, and is relevant regarding hydrogeological characteristics. The hydrogeological model is a piezometric head function which accounts for recharge, drainage and withdrawals. Recharge is dependent on hydrodynamic parameters and on the surface waters including rain. The hydrogeologic model accounts for a certain inertia in the system by specifying dependencies on year $n-2$ for year n, which is characteristic of the Beauce aquifer system. The large size and thickness of the aquifer account for the inertia of the system and its long reaction time. The model's hydrodynamic parameters are calibrated on a 10-year period with the ordinary least squares method. The calibration performs well. Both models are developed in a unique platform in GAMS.

Two hundred climatic scenarios were set-up to perform Monte Carlo simulations in order to explore the effects of climatic uncertainty on the system for the baseline and the open access case. The method implemented consisted of drawing random past years of infiltration and efficient rain (which determines the crops' water needs) and multiplying them by a random *climate change coefficient*, inspired by the results of Boe et al. (2009), to allow for increasing water scarcity in the future. In order to compare scenarios a cost-effectiveness ratio is defined for calculating the cost per hectare of agricultural land and per meter of piezometric level increase.

1.8.3 Main results

The impact of the baseline regulation and the open-access case on piezometric levels and the economic results of farming are explored by Monte Carlo simulations. Alternative

[31] The profit calibration rule enables a perfect replication of observed reference profits, which is not the case for the two other calibration rules.

[32] Note that the zoning has been redefined compared to Chapter 5 which builds on the regulatory zoning

policies are then tested for single climatic scenarios up to 2040. Analysis of the differences between the Monte Carlo scenarios shows that the system is very much influenced by the precipitation.

The current management principle seems to be effective in the short term for maintaining piezometric levels. Implied water coefficients are different according to the region and this justifies the administration's decision to distinguish four zones. The baseline scenario is the least costly of all the tested scenarios (other than the transfer option), which argues for preserving the current management scheme as long as the piezometric levels are acceptable from an ecological point of view.[33]

Our results would not call for a specific strengthening of the constraints, i.e., reduction of the coefficients, in the eastern part of the territory (Montargois and Fusain) as currently discussed within the SAGE. Conversely, the idea (tested in 2012 in Beauce) of limiting the regional differences between the coefficients to a maximum of 10% between Montargois and Fusain with respect to Beauce centrale would come at the cost of a decrease in piezometric levels, because our results show an approximate 30% difference on average between the coefficients in Beauce centrale and Fusain or Montargois.

The open-access case shows a significant decrease in piezometric levels for two of the six regions and a decrease for three others. Figure 1.7 shows that, for Beauce Blésoise, the baseline is stochastically dominant over the open-access case. Beauce Sable shows almost no decrease of its average piezometric levels, because water demand would not change significantly with the open-access case (low shadow values of water in the baseline). The open-access case produces an average gain of +1.5% compared to the reference situation, which is a relative small gain. Changes in cropping patterns mainly affect corn and irrigated corn, while changes in the water application rate are observed for wheat and barley essentially.

We also tested an option that would consider the six regions independently for the calculation of the water coefficient (instead of considering the four regulatory regions). The results suggest that it would have a limited impact on both economics and piezometric levels.

Incorporating inertia into the calculation of the coefficient, i.e., adding the last two years' piezometric heads to the current year's head in the coefficient calculation (lag alternative) seems not to be desirable. When infiltration (precipitation) is on a decreasing trend, the lag instrument "recalls" the better years and provides an overly optimistic signal to the farmers.

[33]Our analysis does not consider the ecological comsequences of different piezometric levels.

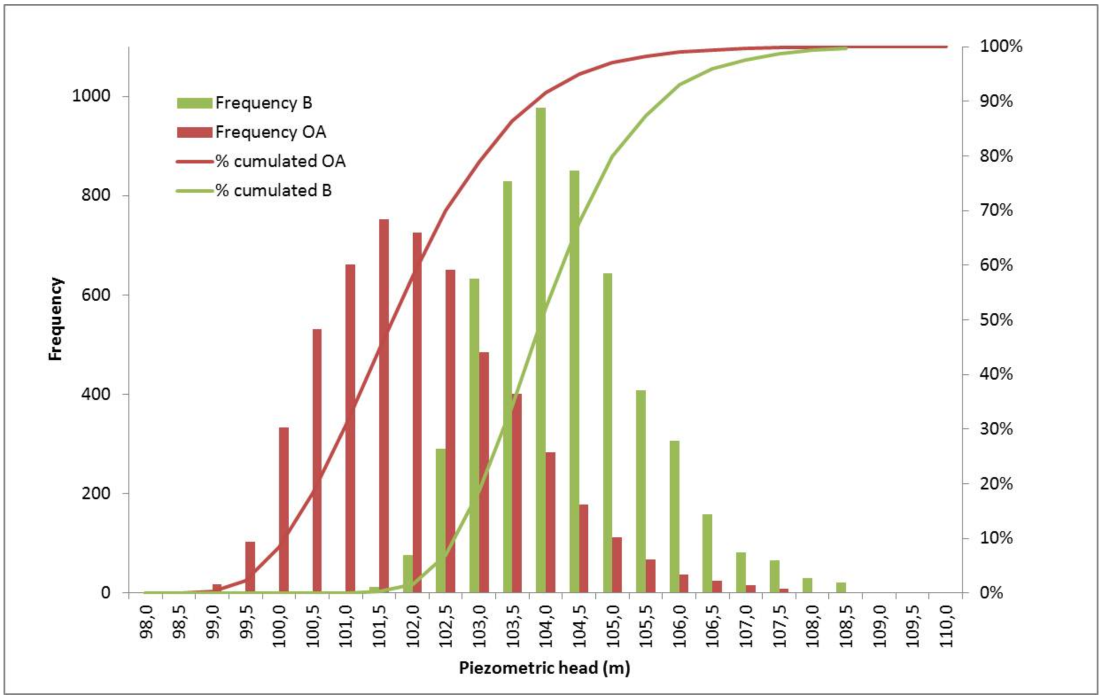


Figure 1.7: Distribution and density of the piezometric head (meters) for the Monte Carlo simulation and all years in the open-access and baseline cases, for the Beauce Blésoise region. OA = Open-Access; B = Baseline

A price-based instrument or tax was tested and consists of varying the level of the water agency fee according to the difference between a reference high piezometric level and the yearly piezometric level. This incentive instrument seems very efficient for reaching higher levels than the baseline in Beauce Centrale. For the remaining regions the differences from the other instruments are small and might not justify the extra cost. Indeed, the cost-effectiveness ratio is the highest for this instrument (33 €/ha/m of head and 20 € higher than the baseline).

The transfer option, which consists of relaxing the water-availability constraints at the regional level, induces significant water exchanges between regions. It does not seem to be desirable, however, because it produces significant reductions in piezometric levels for some of the exporting regions.

The substitution option in the eastern part of the area would not change the withdrawal pattern significantly, because of the high cost of substituted water (0.29 €/m^3) compared to the pumping cost (between 0.06 and 0.08 €/m^3, for potential substitution) and to the shadow values of water (for the potential increase in irrigation). The pumping externality effect (dc_{i2}/dh_n) on water costs is not significant enough to influence the behaviour of farming so as to be equivalent to the baseline case from an environmental point of view i.e. in terms of piezometric levels.[34]

1.9 Discussion: modeling agricultures' use of inputs

We can discuss the methodological choices for representing agricultures' behavior in response to changes in the economical or regulatory context regarding water use and pressure on water resources based on the four essays. Overall, programming models seem more suitable than econometrics because they are less data-intensive and few data are systematically available when it comes to water use or input application. In addition, PM can be used to simulate situations that have not been observed and recorded in the past, which may often be the case with water-related issues (regulation or natural evolution of scarcity). Lastly, programming models have the advantage of incorporating crop-specific production functions which allow us to explicitly link input use with output (yields and quantities).

Among the methodological choices available within programming models, we suggest that the modeling scale should have an influence on the choice of the model specified, depending on the assumption of yield or cost heterogeneity and the subsequent choice of adopting non-linear functions. As seen above, linearity seems acceptable at the farm-scale level as also argued by Chen and Önal (2012) and adopted in a number of previous works, e.g. Gòmez-Limón and Riesgo (2004); Bazzani (2005); Bartolini et al. (2007)).[35] This choice can be made when agronomic and economic data are available at this scale, and when technical constraints are known and are sufficient for representing the observed allocation of resources and cropping patterns. Our research confirms this: MOTAD LP farm models have been successfully implemented to represent the adaptation of farms to global changes. In our case, incorporating risk, with for instance the MOTAD specification, avoids the over-specialization that is often one of the principal criticisms directed at linear programming (Gohin and Chantreuil, 1999). The "jumpy" (or discontinous) behavior characteristic to

[34]In Beauce the increase in water costs can be estimated at 1 €per 1,000 cubic meters for a one-meter increase in piezometric level depth. This is not sufficiently large to internalize the problem of resource depletion, as we can see that piezometer levels decrease in the longer term. For a 1-meter decrease in piezometer level, the water cost per hectare of corn would increase by 2 €.

[35]However, other authors have adopted non-linear specification at the farm scale e.g. Garrido (2000); Finger (2012); Lehmann et al. (2013)

LP appears not to be a problem when simulating global changes at a medium-term horizon, since the dynamics between the reference and the scenario are not represented. Thus "jumpy" changes may be acceptable. From an empirical point of view we could also argue that jumpy behavior is more acceptable at the farm scale (individual decisions) than at the regional scale (aggregation of individual decisions).

At the regional level, sector modeling has to account for heterogeneities in the technologies and resources among the regions, hence non-linear modeling seems more appropriate for accounting for these heterogeneities. In our case the models' property of decreasing marginal yields represents the heterogeneity of the soils in terms of production. The non-linearity property enables us to avoid over-specialization, among other things, and better represents the spatially heterogeneous reality. Non-linear modeling also mathematically enables exact calibration, and this avoids the problems of aggregation bias. To summarize, we believe that PMP models are more suitable for modeling the regional scale, while LP models are appropriate when modeling farm-scale behaviors. However, linear models do not allow for intensive direct margin adjustment if different activities are not suggested, i.e., explicitly included in the model.

From a practical view point, the solving of PMP models is more complicated than for PL models because the underlying mathematics are more advanced, owing to the need for non-linear solving. However, this is no longer a problem because of new softwares, i.e., GAMS and non-linear solvers. In addition, these models involve limited calibrating regions (i.e. not all problems can be solved, some are untractable), plus adding a number of steps required to verify the conditions under which a solution may exist and its uniqueness (see Mérel et al. (2011)). The more binding-constraints, the more complex are the systems which have to be solved. The complexity of the test conditions are time-consuming and might deter an analyst who needs to work with more than three inputs. Comparing the quadratic with the generalized CES model, the CES has a calibrating region which is larger than the first (Mérel et al., 2011).[36] Lastly, positive mathematical programming is self-calibrating in the sense that the analyst does not need to spend time on each model in order to adjust the constraints, as with LP farm-scale models. Once the model specification and the calibration conditions are explicitly formalized, the model can be calibrated to a large number of data sets without intervention, i.e., automatically by the programming.

The following table presents the characteristics of the various models discussed above. We discuss our work in more detail in the Perspective section.

[36] This is also a consideration when choosing between different functional forms

Model	Calibration	Arbitrary data	Over-specia-lization	Jumpy behaviour	Validity of far from reference simulations
Linear models	Technical constraints (TC)				
*Basic LP	-	-	Yes	Yes	Yes, but the
*Historical Crop-mixes	TC	-	Yes	Yes	problem is the farm
*MOTAD (risk)	TC+ Risk aversion	-	Less then basic	Yes, less	typology stability
*MOTAD MonteCarlo	TC + Risk aversion	-	LP	Yes	
Non-linear models					
*PMP "Howitt form"		Diag. elem. set to zero	No	No	No
*PMP Merel - Fix prop.	Exact	-	No	No	No
*PMP Merel-CES		Elasticity of substitution	No	No	No

Table 1.1: Summary table of selected PM models

1.10 Conclusion

This thesis assembles studies that deal with the issue of agricultural responses to changes in the economic and regulatory context. Those studies were developed intermittently between 2004 and 2012.

Its contribution is twofold. The first is a study of how to adapt models of economic production (or agricultural supply) to the issue of water management, including a connection with biophysical models. The second contribution is a series of policy-oriented results that show how agriculture, principally in Beauce and Alsace, can adapt to various global-change scenarios and to instruments aimed at regulating agricultural water use and contamination pressures.

In this conclusion the methodological aspects of developing and implementing economic programming models in this context are discussed. The essays are illustrations of the value of economic programming models for representing the responses of farming to changes in water uses and pressures. We show how different methodological choices in the scale and model specifications were selected so as to fit the case studies and policy questions. The second part of this conclusion is devoted to summarizing the policy findings related to each of the problems and case-study settings.

1.10.1 Key methodological points

The first essay showed why economic approaches that concentrate on the behavior of farmers are necessary for assessing the evolution of land use and the long-term state of groundwater resources, and how this can be achieved by connecting a detailed economic model with biophysical models. From a modeling viewpoint, the LP farm models developed in Chapters 3 and 4 show interesting abilities for simulating the effects of a significant number of changes that require a high level of breakdown in the model. For instance, energy consumption and price have been isolated in the gross-margin specification, and used to account for the effect of energy-price changes in the model. The results they provided on cropping patterns and practices have been well received by experts, which can be considered a validation.[37] One of the reasons these economic models have proved to be relevant is that a lot of specific farm data (economic and technical data) were recovered during interviews with typical farmers or were provided by agricultural experts. Moreover LP seems to be suited to the context of individual farm modeling for a medium-term future (about 10 years) with only limited structural change. To the best of our knowledge there are no other cases of LP farm-scale models in the literature that have been developed for this type of exercise in the context of modeling agriculture's impact on groundwater.

However, in different settings this approach might have faced several limitations. The main limit of linear farm programming models is the relative inflexibility that characterizes these models and, as a consequence, the limited possibilities for farming to adapt. This inflexibility refers to the limited number of activities, including technological alternatives, that the model incorporates and that can be "chosen" by the model in certain scenarios, because alternatives have to be explicitly incorporated by the modeler. In our case, if the model had been more flexible[38] in terms of nitrogen application on crops other than corn, the results might have been different. Possibly reductions in fertilizer application in other crops would have reduced the extensive margin adjustments (changes in crops)[39] and reduced the overall costs of scenarios. A certain portion of the inflexibility can also be attributed to farm-scale modeling, which in our case requires that the total cropped area remains fixed for a given farm type. This prevents any size change in the models (for instance expansion of

[37]This is worth noting because linear programming is sometimes referred to as being an old and outmoded method.

[38]This would have been possible even with LP by multiplying the number of activities using different levels of nitrogen application

[39]The extensive margin adjustment refers to a change in crops, whereas the intensive adjustment refers to a change in input level while crop acreages remain constant. The terminology of extensive/intensive margin is discussed in Chapter 5.

farm size). This constraint could have been eliminated while incorporating the cost of land and the total cropped area as a variable of the model. But this would require an estimation of the cost of land or a simulation of the cost of land within a larger model designed to simulate its market.

While the LP approach developed here is suitable for representing the impact of price-based instruments on input use, it does not seem to be relevant to the modeling of voluntary agro-environmental measures, which already exist in parallel with regulatory measures (control measures, see Appendix 3.8, Chapter 3). This is because of the need to specify associated costs (or benefits) that are not necessarily known, especially non-accounting costs.[40] Moreover, diversity of their adoption within a farm type seems inevitable for these types of measures and this cannot be represented using our farm-type model approach. In the present approach, these measures such as CIPAN crops (intermediate crops that capture nitrates) are adopted either totally or not at all, depending on their gross margins, which is obviously not a good representation of the reality. In Chapter 4 the impact of uncertainty of context scenarios on the response of farming is explored. Several model parameters (prices of products and inputs) are defined as stochastic variables. They are randomly drawn within a predefined interval and some variables are defined as dependant from others in order to impose a correlation in the random draws. Combining Monte Carlo simulations with an LP farm model represents a partial response to the traditional "jumpy behavior" criticism directed towards basic LP, since it enables us to explore the effect of uncertainty on model responses. The response that the simulation provides is not deterministic because it provides different possible outcomes, which represent the uncertainty. This variety of possible futures, e.g., of possible cropping patterns, is relevant to the envisioning of possible agro-environmental measures that would be consistent with future cropping patterns. This could be useful to decision-makers who have to plan programs of measures designed to achieve a “good” status of water bodies under the WFD.

In Chapters 5 and 6 we build on Positive Mathematical Programming, which has several advantages including being less data-intensive than LP and enabling a perfect replication of the reference situation. This is particularly valuable in the Beauce case study, focused on irrigation, for which few data have been systematically collected. Our non-linear models show linear costs and constant elasticity of substitution between land and water with decreasing marginal yields in order to account for heterogeneity in soil properties. Several

[40] For instance non-accounting costs such as individual preferences of adopting less intensive practices. This would require empirical data analysis to understand the determinants of the adoption of agro-environmental measures

variants are developed, which are calibrated on supply elasticities so as to control supply responses and/or to observe accounting profits so as to replicate observed profits. They are also calibrated to the agronomic responses of yield to water application intensity, in order to correctly represent the response of quantities to applied water, since this is an adaptation possibility when modifying the availability of water to farming. The model's specification and calibration enable the use of all the data available on irrigated agriculture in France without requiring additional information, which is not systematically available. The model developed here enables simulation of the effect of increasing water scarcity on agriculture's economic results and on the adaptation margins of irrigated agriculture, with and without water-transfer possibilities. The methodology proposed in Chapter 5 could be used in several applications. The first would be to explore the effects of reductions in water availability on agriculture as a consequence of policy, as illustrated by our case study, or as a consequence of climate change.[41] A second type of application would be the simulation of global change scenarios (joint increases in product prices, policy changes such as the CAP reform, and reductions in the availability of natural water).

Chapter 6 develops a holistic hydro-economic model. It enables simulation of a wide variety of scenarios and dynamic analysis of the results, because the model allows simulation of a continuous series of years. Our calibrated modeling approach provides interesting results and analyses for local decision-makers. Its main advantage is to offer a single platform that accommodates both detailed economic and hydrogeologic modeling, which allows feedbacks to be incorporated in the models during simulation, along with exploration of the impacts of a variety of simulations. This shows that economic programming models can be conveniently used to connect with bio-physical models to explore the impact on both water resources and water users of alternative water policies, including the analysis of the open-access case.

1.10.2 Policy implications

The main motivation of the research undertaken is to determine the real-world implications of farming's responses to changes in the overall economic and regulatory contexts. In the first essay, the motivation of the initial overall project was to assess the future level of groundwater contamination by nitrates in the Upper Rhine aquifer, and the objective of farming adaptation was a secondary but necessary goal on which we were particularly

[41] Climate change might cause a reduction of less than 20% in runoff, i.e. in the water resource, in Central and Eastern Europe (Milly et al., 2008). As such, its impact can safely be assessed by PM methods, which are suitable for simulating moderate changes in model parameters as opposed to very large changes.

focused. The economic model's results served as input to the biophysical models and were developed in this perspective. The main empirical findings can be summarized as follows:

- The global change scenarios (Business as usual; A1 - Liberal orientation; and B2 - Environmental orientation) have a significant impact on cropping patterns, mainly on the French side of the Rhine where the corn areas decrease to the benefit of three-year wheat/rape/corn rotation patterns.

- Less nitrogen-intensive corn practices will be adopted mainly under the B2 scenario where the effects of energy and fertilizer prices make less-intensive practices more economic than intensive ones. However, the B2 scenario turns out to be the most polluting, in terms of nitrates in water, because of the development of biofuel crops.

- Economic instruments such as nitrogen taxes or nitrogen residue taxes do not seem effective in abating nitrate contamination at a reasonable social cost in the Alsace case. Other instruments such as norms might be more efficient. However, the relative inflexibility of our models may have masked some of the farmers' adaptation margins and overestimated the costs of the tax.

In the second essay, the main focus was to develop a method that accounts for uncertainty in the environmental (pest attacks, climatic change) and economic or regulatory (product and energy prices, CAP ...) contexts, in the assessment of the impact of nitrate contamination by farming. The overall idea was to explore whether the environmental state and the objective of pollution abatement could be targeted with sufficient confidence to ensure the success of water-protection policies.

- Allowing for a large uncertainty in the overall context, we show with confidence that the level of contamination will be reduced in comparison with the reference situation. The contamination will not be very different from one scenario to another even when allowing for uncertainty within the context scenarios (Monte Carlo simulation). Accordingly, decision-makers could target a well-defined contamination level and confidently build programs of measures to achieve this level.

- The corresponding cropping patterns, although slightly different according to the Monte Carlo simulations, show similar patterns. This is also an interesting result, suggesting that crop-specific practices can be encouraged and designed to reduce pollution.

In the third essay, we were concerned with the adaptation of Beauces' agriculture to the constraints of increasing water scarcity.

- In Beauces' irrigated farming, reductions of up to 30% of water availability (quotas) would not have a significant economic cost (less than 1% reduction in profits) to the agricultural sector as a whole, partly because irrigated area represents only a small share of total cropped areas. Quite significant changes occur in terms of cropping patterns, with irrigated corn reduced to the benefit of cereals.

- The responses of the agricultural sector were broken down under three margins - the super-extensive, extensive, and intensive margins - representing different adaptations by farming (reductions in irrigated areas or the application of water). We found that about 20% of the response to reduction in water availability consists of intensive margin adjustments, i.e., reduction in the water application rate per crop. Our results suggest that intensive-margin adjustments need to be taken into consideration when modeling the effects of water scarcity on agricultural systems. This is an important point, as many large-scale policy models are not currently geared towards modeling such adjustments, a prime example being the European CAPRI model.

- From a policy perspective, the result on the intensive-margin adjustment (Chapter 5) should motivate regulators to augment their knowledge, or at least ensure that this knowledge exists, concerning the yield response to water. If farmers do not know how their crops will react to a slight reduction to water, they might not explore this adaptation path. Detailing these findings in farm-scale approach that incorporates risk might be envisioned.

The last essay is an attempt to incorporate in a single model the hydrogeologic and economic representations of the Beauce aquifer, in order to explore the trade-offs in alternative water-policy instruments.

- The current water regulation that consists of multiplying a water quota by a coefficient calculated from the yearly piezometric heads of four of the aquifer's regions seems to be efficient in the medium term and considering climate change, compared to the open-access case.

- Moreover, the cost of the water-availability constraint, i.e., regulation for farmers, is reasonable and amounts to about 1.5% of baseline agricultural profits.

- Alternative instruments have been designed to find a more cost-effective water regulation policy: a coefficient calculated from the preceding years instead of the current year; a tax on water use indexed to the depth of the aquifer; a transfer option between regions; substitution possibilities. They all seem to be less cost-effective than the baseline, but the tax instrument seems effective for achieving higher piezometric levels. As such, this instrument might be considered by decision-makers should the ecological standards require higher piezometric levels than the one ensured with the baseline.

1.11 Perspectives

1.11.1 On the behavior of farming with respect to water constraints and costs

There is still much to be done in representing the behavior of the farming sector and of individual farms with respect to their choices of water allocation, withdrawal, and fertilizer use.[42] This topic will remain a major one, given the important challenges of water management in the face of rising water and food demands and the issue of food security in some parts of the world. We believe this is also a major challenge for supply and partial or general equilibrium agricultural modeling. For instance, the CAPRI European agricultural model, which covers all the administrative regions in Europe, does not account for water as an input nor consider it from the resource-constraint point of view, even though in several southern-European areas water is one of the main binding constraints for agricultural production. Integrating it might completely change the response of agricultural supply.

We discuss three main avenues for improving representations of the behavior of farming with respect to water use. The first lies within mathematical programming and the challenge of correctly representing the behavior of farming with respect to water allocation in the face of increasing water scarcity. The specification of the elasticity of substitution, which is important to the model's behavior regarding water and land allocation, could be improved: the literature on this parameter is relatively scarce (no values found for France) and never specifies crop-specific elasticity of substitution. One solution would be to calibrate this parameter and make it crop-specific. A second solution would be to estimate this parameter

[42] and pesticide use, although we did not consider these contaminants

from large data-sets, using econometrics. One could also argue that this parameter may not be fixed, but may change with the production function.

A second issue is linked to the disadvantages of PMP models in not necessarily being reliable for simulating situations that are far from the calibration situation. For instance, when far from the reference, the behavior of the Constant Elasticity of Substitution (CES) function is not a decreasing one in water levels above a maximum "agronomic optimum", for a given fixed land input. Representing this property would be more consistent from an agronomic point of view. However, it is a minor problem within the economic model if water has a decreasing marginal benefit, and implies that water application is not exaggerated. A related point is that there is no particular correspondence between the production functions of the irrigated and rain-fed alternatives of the same crop. For instance, if no water is applied in the irrigated alternative, its production function does not give an output similar to that from the production function for the rain-fed alternatives. In practice, this is not a major problem, since the model would not choose the irrigated alternative together with very low irrigation, but it might set a limit to overall model consistency. The Rohm and Dabbert approach (Röhm and Dabbert, 2003) is a partial response to this problem: it suggests calibrating the alternatives for the same crops, e.g., organic/conventional, together, and adding a cost term to distinguish the alternatives. However, in our case irrigated and rain-fed alternatives for the same crops are already specified by several identical parameters.

This issue of "far from the reference" model behavior could be explored to check on and improve overall model consistency and its ability to simulate "far from the reference" policy experiments. These explorations would also enable the definition of what, for a given model, is "far from the reference": is it + or -50% of the water resources or price availability? These situations could be encountered in a market- or transfer-experiment setting (as tested in Chapters 5 and 6): water exchanges from regions with low to high marginal water benefits might imply a significant increase or decrease of local water availability that would reach a far-from-the-reference, i.e. calibration situation. In such cases PM models may be less reliable. However, if the policy's focus is on adaptation to climate change or to changes in the water-uptake regulations these might be continuous and not too remote from the reference (changes in the range of +/-30%).[43]

[43] But some changes related to the implementation of the Water Law and the new authorized *"volumes prélevables"* correspond to reductions of more than 50% of the reference withdrawal in some southwestern basins (Hébert et al., 2012).

The third perspective refers to the specification of models at regional scale while some constraints arise at the farm scale. In such cases the assumptions of Chapter 5 and 6 concerning the homogeneity of farms within regions must be altered if too much heterogeneity exists among the farms.[44] Farm-scale modeling is then required. This may also become necessary in order to correctly represent water-related constraints (access and cost of water), for instance, if individual allocations are known to differ according to the farm and the area. We could model all the individual farms of Beauce based on the database of the *Registre Parcellaire Graphique* used at the aggregate level. The self-calibrating property of PMP enables the modeling of a large number of farms (about 5,000 in this case). However, a number of checks must be made, to ensure that calibration is feasible.[45] PMP appears to be an interesting method for modeling very large numbers of farms, but this has not so far been attempted or tested, to the best of our knowledge. Concerning the Upper Rhine and Beauce case studies, one method would be to compare results from both the LP farm-scale approach and the PMP regional-scale approach.

A fourth perspective is related to increasing our knowledge and comprehension concerning how farmers really reallocate water when they face a change in the constraints or cost of the resource. Complementary approaches to mathematical programming modeling, such as field studies, policy exercises or experimental economics, could be envisioned, by way of adopting a micro- and positive approach to our problem, e.g. Bouarfa et al. (2011). The diversity of adaptations could also be analyzed and in this way the heterogeneity among farm types or among regions might be better envisioned: for instance, the impact of ownership or inheritance status on allocation decisions. One of the main arguments for these "micro" approaches is that they could, in theory at least, accommodate the simulation of far-from-the-reference changes.

A particularly interesting avenue would be to couple both PM and field-study approaches in a "research-action" perspective. The idea would be that the processes and results would feed each other. The field study would assemble the stakeholders (public decision-makers, farmers, associations) and have them suggest adaptations, both from an institutional and from an individual (farm) viewpoint, to changes in the natural or regulatory constraints. These could be tested by means of PM models to provide some insights to the group regarding the overall response of the system. At the same time, feedback from the group of experts could help to improve the behavioral characteristics of the model.

[44] As explained in Chapter 5, agriculture in Beauce is particularly homogenous with more than 90% in the same FADN farm type

[45] Calibration region, see Chapter 5 and no activities set to zero

1.11.2 On considering uncertainty and risk in the behavior of farming

Concerning the issue of uncertainty in the assessment of the impacts of global change, discussed in Chapter 4, we might adopt a different perspective that would be more focused on representing the behavior of farmers in the face of increased uncertainty regarding global change. In other words, we could incorporate in the model the expectation that the uncertainty perceived by the farmers may be different (greater) than the uncertainty that characterizes the reference situation. Indeed, in Chapter 4 the revenue uncertainty that characterizes each crop is the standard deviation of the price times the yield from 1995 to 2003. The one that farmers will be expecting by 2015, and the associated level of risk, may be greater - and this could be taken into account in the models.

A second approach would be to increase the temporal disaggregation of the conceptual framework adopted, in order to include short-term adaptations to water scarcity. e.g., intra-annual adaptations affecting water application. These intra-annual adaptations occur when crops have already been sown and the cropping patterns remain fixed. They consist of adjusting the application of irrigation water according to the weather, which is unknown at the beginning of the growing season, i.e., when decisions about the cropping patterns are made. This specification would be relevant in a hydro-economic setting such as the one discussed in Chapter 6 because it is the actual water withdrawal, and not merely the anticipated water requirement, that is of importance, since it is an input parameter for the hydrogeological model. Such refined models would also enable the testing of alternative policies and instruments that are more time-disaggregated, for instance, a water right that would evolve along with the intra-annual state of the water resources.

1.11.3 On quantitative hydro-economic modeling in France

To correctly represent the whole "hydro-economic system" and understand the joint evolution of such systems, it will be necessary to further integrate both the economics of farming and institutional choices on water allocation, and incorporate them in a biophysical (agronomic and hydrologic) model. Examples are provided in Chapters 3 and 6. This field of applied research is rapidly expanding[46] and remains largely site-specific. However, to the best of our knowledge there are no large-scale hydro-economic models in France[47] as there is in

[46] a citation report from the ISI Web of Knowledge shows a slight increase in publication since 2007 and a significant increase after 2010 in topics or titles including the term "hydro-economic"

[47] the PIREN Seine model is concerned with water quality. However, it focuses mainly on the development of the biophysical compartment (Ledoux et al., 2007)

Spain or California with the CALVIN and SWAP models (Howitt et al., 2010), whereas there are large-scale irrigation networks in France (Bas-Rhône Languedoc, Canal de Provence, Southwestern systems) as well as groundwater bodies with quantitative-management issues (Beauce, Nappe Profonde de Gironde). These areas could benefit from hydro-economic models, both to assemble available knowledge on biophysical and economic processes and to assess the impacts of alternative policies. The potential interest of decision-makers in these results is also a major question, if not a prerequisite that needs to be explored before starting any such work.

1.11.4 On the assessment of multiple environmental policies

Another major challenge of these models is to integrate the multiple externalities of farming on water resources (water use or pressure). Indeed, it is more appropriate to assess the combined impact on nitrogen and quantitative management in order to have a response that is closer to reality, and that is able to detect the probable synergies or competitions and trade-offs between policies and increases in natural constraints. This is important because marginal input allocations are not independent. For instance, if corn is irrigated the fertilizer dose must also be adjusted, because the overall yield that is targeted by the farmer is increased compared to a rain-fed crop. Ideally, all economic and environmental policies should be tested in tandem in order to foresee these combined effects. This is illustrated by one of our results in Chapter 3, which suggests that an environmental change (scenario B2 of SRES, which is associated with lower greenhouse gas emissions) might have a weaker impact on water quality than the liberal scenario. This need is also illustrated by the growing number of studies related to integrated environmental assessment. If these constraints and effects are not considered together, poor decision-making may be promoted and some potential competition or substitutions among environmental policies might be overlooked.

Chapter 2

Economic calibrated agricultural supply models to inform water management and policy: a review

2.1 Introduction

There is a growing need to assess the effects of water policies and global changes on both water resources and agriculture itself. This calls for interdisciplinary approaches such as hydro-economic modeling (Harou et al., 2009). The challenge for economists is to adequately understand and represent the behaviour of farming with respect to water use and allocation among crops in order to assess their economic impacts and the adaptations that might be implemented both by farmers and by institutions in reaction to changes.

Agricultural economics has developed various approaches based on production economics[1] (Beattie et al., 1985) to model the derived demand for the inputs to agricultural production including water and nitrogen. There are various empirical economic methods available for modeling or portraying agricultural water demand: programming models; econometrics (Moore et al., 1994; Hendricks and Peterson, 2012); field experiments (Bouarfa et al., 2011); Data Envelopment Analysis (Frija et al., 2011); hedonic pricing (Faux and Perry, 1999); contingent valuation (Storm et al., 2011). Analytical models are also used on a theoretical basis but there has been no attempt to fit them to any observed data i.e. the allocation of resources (Burt, 1964; Rubio and Casino, 2001; Koundouri, 2004b; Koundouri and Christou, 2006). The other types of models used in a water management perspective are what we might call *heterodox* economic models: agent based models or object oriented models, whose assumptions are different from the maximization or minimization of utility (see for example Berger (2001) and Brémond (2011)). Among empirical models the most commonly implemented approaches are econometrics and programming models, with a greater number of published programming models (Scheierling et al., 2006).

Econometrics constitutes a pure *positive'* approach. Its aim is to understand economic phenomena by identifying determinants (e.g. Green et al. (1996) who seek to understand the irrigation technology choices) along with, sometimes, the objective of predicting the evolution of dependent variables. Econometric models designed to represent the observed behaviour of farmers are estimated based on observed data and their advantage is a best fit of the observed data with little or no constraint on the functional form. One of the main limits of econometrics as applied to supply modeling is that it might not be valid when

[1] where a production process is characterized by a technology, a production function, costs of inputs and product prices

simulating policies or parameter values, i.e. prices, that are out of the range of previously observed situations (so called "out of sample" issues) (Lichtenberg et al., 2010). Also, they do not specifiy crop-specific production functions, consequently the inputs are not allocated to one activity or crop in particular, which is a problem for the environmental / externality analysis of farming systems. Another drawback of econometrics is that it often provides an overly high level of aggregation across different small regions or farm types.

Economic programming models aim to represent the agricultural production process and thereby the observed allocation of resources and the responses to changes in policies or modified input constraints. They differ from pure econometric models, because they contain an explicit production function in a “normalized” functional form integrated into the utility/profit function. This may be considered an arbitrary constraint, but it will ensure the relevance of out-of-sample simulation which is a major advantage when addressing the adaptation of farming to changing constraints (be they exogenous global changes or policy changes). It also enables calibration of the model with less data than would be needed for an equivalent econometric model. Programming supply models are consistent with the neo-classical theory since they make use of mathematical formalism and build upon methodological individualism.

The economics of water use in agriculture have experienced an accelerated development during the 1960s owing to the concern for valuing supplied water and for estimating the demand for irrigation water in the context of dam construction or water transfers, as part of water planning (Hartman and Anderson, 1962). Linear programming was among the methods implemented to deal with these questions (Shumway, 1973). In parallel, a long tradition of using mathematically calibrated models for agricultural policy analysis has developed since the 1950s (Samuelson, 1952; Boles, 1955). The various applied implementations of linear programming were discussed in detail in the book by Hazell and Norton (1986). So called "residual imputation" using linear programming was applied to irrigation water use to infer water demand and to develop a water-use profit function (Booker and Young, 1994). In the 1990s, further developments, in particular, non-linear “Positive Mathematical Programming”, took place to correct several of the shortcomings of linear programming (LP) models, as discussed later. It implied several innovations in terms of solutions and calibration that were made possible by advances in mathematical software[2] developments that provided solutions to non-linear problems.

[2]such as GAMS (Generic Algebraic Modeling System)

In this chapter we review the literature on agricultural supply modeling for addressing water management issues, which we will call WPM (Water - Programming Models). Macro-economic models, i.e., partial or general equilibrium models that relax the assumption of inelastic agricultural product demand are excluded.[3] Examples of partial or general equilibrium models applied to water analysis are Gomez et al. (2004); Frisvold and Konyar (2012) and Calzadilla et al. (2011). Dudu and Chumi (2008) review macro-economic models concerned with irrigation water management.

The outline of the chapter is as follows. The first section describes the various topics related to water management that employ WPM approaches. The second section develops the characteristics of the models and discusses the normative and positive perspective of modeling, and the third section discusses the aspects related to the integration of water-related production functions into the economic models. The fourth section discusses the ways in which risk and uncertainty can be taken into consideration in models and why they are relevant to water management related applications. The fifth section concerns the spatial scale and the aggregation bias. The last section suggests a research agenda for agricultural supply modeling applied to water management.

2.2 Topics addressed by WPM

This section reviews the topics for which programming models have been developed. Some model development concern more than one topic. For instance Iglesias-Martinez and Blanco-Fonseca (2008) examined technology adoption in combination with water pricing.

WPM are sometimes associated with hydrogeological, hydrological, reservoir operation and/or crop growth (agronomic) models to better represent bio-physical processes that influence economics or to observe their impacts on water resources. They are commonly referred to as hydro-economic models (see Harou et al. (2009) and Brouwer and Hofkes (2008) for reviews). WPM can also be implemented within a larger economic modeling framework that incorporates partial or general equilibrium models. Ejaz Qureshi et al. (2013a) show, based on the Australian example, how water scarcity as a consequence of climate change impacts food exports and global food security.

[3] except for comments on the supply module of these models

2.2.1 Water scarcity, drought and climate change impacts on agriculture

WPM can be used to assess the economic costs and associated adaptations to increasing water scarcity conditions that result from drought or the effects of climate change. The impact of climate change is an increasing common application for PM: see Connor et al. (2009); Medellín-Azuara et al. (2010); Connor et al. (2012); Finger (2012); Lehmann et al. (2013); Dono et al. (2013); Ejaz Qureshi et al. (2013b). Dono et al. (2013) show for instance that changes in climate variability will increase the agricultural demand for groundwater because surface water will become a less reliable source for future water supplies. Increasing water scarcity can also result from a strengthening of agricultural water use regulations in response to growing urban and environmental water demands, e.g. the Water Framework Directive. In this case the models are used in simulations with varying levels of water resources. Sunding et al. (2002); Iglesias et al. (2003); Frisvold and Konyar (2012) have respectively explored the effects of reduced water availability using a PMP model, a dynamic recursive model, and PMP with endogenous prices.

2.2.2 Irrigation water pricing

Water pricing has been extensively analyzed and discussed by agricultural economists. Economic theory encourages the adjustment of prices to marginal revenues if water is scarce to incite more valuable uses of water among users and to ensure maximum social welfare. The challenge of "getting prices right" is a major one, particularly in the WFD context which calls for full cost recovery.

Water pricing experimentation has traditionally been approached using econometrics e.g. by Moore et al. (1994) who estimated water price elasticity by observing cross-sectional and panel data. Other examples include Schaible (1997); Albiac et al. (2005).[4] However, Doppler et al. (2002); Gòmez-Limón and Riesgo (2004); Bazzani (2005); Bartolini et al. (2007); Viaggi et al. (2010); Balali et al. (2011) have employed WPM to analyze the issue of water pricing. Dono et al. (2010) use a linear programming approach incorporated within a hydro-economic model to explore the effect of surface or volume-based payment for irrigation water. They show that volume-based payment can induce a shift towards

[4] Albiac adopts an original method to simulate water pricing reform. It is a multistage, multi-output, normalized profit-maximizing approach. Stage one is based on disequilibrium theory i.e. producer equilibrium decisions account for static long run expectations of fixed resource opportunity costs, which they incorporate in the behavioural production decision. Stage two builds the long-run restricted-equilibrium model (based on observed accounting costs), stage three is the establishment of a linearized quadratic model.

groundwater at the expense of the budget balance of the water-supply service. Iglesias-Martinez and Blanco-Fonseca (2008) explore the impact of pricing policies on the level of technology adoption. Conradie and Hoag (2004) review programming models that focus on irrigation water values and related pricing and Johansson et al. (2002) review irrigation water pricing.

Note that in theory a price increase is equivalent to an increase in the level of constraints (i.e. an increase in water scarcity) and this explains the use of similar modeling choices. Water demand functions can also be derived from price simulations. Several authors have used the results from WPM to estimate the coefficients of standard pre-defined water demand functions (linear or quadratic in prices), because these can be easier to use for further analysis see Vaux and Howitt (1984).

2.2.3 Markets

WPM can also conveniently be used to simulate water markets and the trade gains of potential water markets. Markets or the potential for a market can be assessed using the water demand functions of different farmers or different regions. Market clearing conditions are drawn from the water demand functions, transaction costs and resources constraints. Examples are various in the Western United States: Booker and Young (1994) modeled the interstate and intrastate market opportunities accounting for urban, hydropower, and agricultural water uses, Taylor and Young (1995) assessed the foregone benefits of water for agriculture in an interregional and inter-sector water-market setting, Turner and Perry (1997) assessed the effect of markets on the potential for water-saving technologies, and Rosegrant et al. (2000) modeled water markets within a hydro-economic model. Garrido (2000) is one of the first examples of PM applied to water market potential in Spain. Arriaza et al. (2002) and Gòmez-Limón and Martinez (2006) explored the potential of local water markets considering respectively the expected and multi-attribute utility theory. Another example is provided by Calatrava and Garrido (2005) who also considered uncertainty employing discrete stochastic programming (DSP). Technically two modeling steps are distinguished. The first corresponds to classical supply modeling which simulates production decision by irrigators. The second model simulates the market itself. Australia is also the locus of recent research projects that test for water markets by using PM (Ejaz Qureshi et al., 2013b).

2.2.4 Technology adoption

One of the responses of agriculture to water scarcity is to change its irrigation technologies. Drip irrigation is known to be more efficient than sprinkler irrigation, which is more efficient than traditional or furrow irrigation. The efficiency is measured here by the return in output per unit of water application. However, the selection of a particular irrigation technology depends on various criteria including the agronomic conditions. Some studies have employed PM to model the adoption of new technologies. One static model example is Medellin-Azuara et al. (2012). Gardner and Young (1988) used LP to evaluate the cost-effectiveness of six alternative techniques and technologies to reduce water use and related salinity in the drained water. Carey and Zilberman (2002) developed a dynamic investment model of technology in a real option setting.[5] Isik (2004) also used real options to model the adoption of conservation programs by farmers in a context of uncertainty.

2.2.5 Foresight or global change impact

In this regard, the aim is to form a picture of the adaptation of agriculture to combined changes in the bio-physical, regulatory, and economic environments. This application is less common for PM models. The objective is to develop a picture of agricultural supply, cropping patterns, and input use - in particular water use at a future time horizon - given a set of modified input parameters that have been characterized. This characterization can be performed based on arbitrary assumptions or on a foresight exercise. A future scenario can be characterized by changes in Common Agricultural Policy, prices, and input use constraints. An example is provided by Shumway (1973) who assessed the level of water demand by the farming sector up to 1980. Bartolini et al. (2007) combined future scenarios with alternative water pricing policies to assess the relative effect of each change; Graveline et al. (2012) assessed the impact of global change scenarios on water use and nitrate leaching impacts.

[5] Real option theory builds on financial optioning and is a development of the Net Present Value concept that allows consideration of the possibility of making choices later (“options”). This theory is characterized by the introduction of uncertainty, irreversibility, and flexibility in management and time into the classical Net Present Value (NPV) framework. It considers the decision to invest not as a “now or never” decision but as an option to wait and make the investment in the future when more information is available or when the variables of the problems (e.g. product prices) have proved to be more attractive. With time the uncertainty might change and postponing the decision could lead to higher profits: see Dixit and Pindyck (1994)

2.2.6 Optimal water allocation: a slightly different perspective

There is a relatively abundant literature on designing, planning, and operating water resources systems. These include the withdrawal and allocation of water across different resources and users. The majority of works are focused on the optimization of surface irrigation networks (Reca et al., 2001; Bharati et al., 2008) or on the optimization of cropping patterns from a planners' or irrigation association perspective e.g. Montazar and Rahimikob (2008). Lehmann et al. (2013) provides a recent example of optimal farm management in the context of climate change. Their model incorporates detailed information on crop responses to both irrigation and fertilizers application and accounts for risk, which is assumed to increase with climate change.

The main difference from the models discussed in this paper is that they follow a normative or engineering perspective i.e. *what is best?* whereas calibrated models seek to represent the behaviour of farmers or farming. The objective, here, is to examine how to improve the allocation of water in time and space to satisfy optimization criteria. Particular applications may be irrigation scheduling (McGuckin et al., 1987), dam operations, and conjunctive surface and groundwater use. For this type of application the time scale applied is often less than a year to account for variation in water supply and crop needs according to the season. These applications often involve dynamic optimization procedures and sometimes account for uncertainty in weather-related parameters (precipitation, water requirement per crop for a given year). Models are often connected to hydrological and engineering models such as reservoir operation models, to account for the processes of water supply and of the behaviour of other water use sectors, e.g. industry and drinking water. As such they are often referred to as hydro-economic models.

2.3 The model

2.3.1 The objective function

The objective function is maximization or minimization of the utility, often assimilated to profit or expected profit, in the case of risk. More elaborate indicators are sometimes used when more than one attribute is considered in the objective function. Gòmez-Limón et al. (2003) suggest that the decision-making process is driven by other criteria than simple profit maximization, for instance, minimization of family labor. Bartolini et al. (2007) develop LP with multi-attribute utility theory (Keeney and Raiffa, 1993) by specifying an alternative objective function that is the sum of weighted attributes including profit, labor and diversification. Agriculture is a specific production process since some farms employ only on-farm labour and have limited resources and liquidity that could be formalized as constraints. However this is rarely represented in the objective function. In the large majority of cases yearly profit (or net revenue) is considered: the yearly revenue (prices and quantities of harvested products) less the variable costs. Variable costs are those that are attributable to a specific field production or livestock. Few studies provide details of what they actually consider to be variable costs (machinery costs for instance can be viewed to a certain extent as structural, i.e., attributable to the whole farm or as specific variable costs, i.e, attributable to a single crop).

The formulation of the general model has been discussed in Chapter 1.

Two different activities i are always considered for the rain fed or irrigated technology of the same crop. Activities may also distinguish different irrigation technologies. To our knowledge, there are no livestock activities that have been incorporated into WPM. WPM should be able to represent (i) the change in land allocation between crops and alternative activities (sometimes there are several technologies that may suit one crop, for instance different irrigation technologies), (ii) the substitution between inputs, particularly between several water resources or between irrigated land and water. If there is a substitution possibility between water and land, the water application per unit of land can be adapted. The first ability always exists in WPM, but the second is not always present. In the latter case, production function are of Von Liebig type i.e. inputs are specified in fixed proportion. In other words for a given output, inputs are required in fixed proportions whatever the costs may be and $q_i = x_i y_i$ and a unique input is considered in the production term (q_i) (often land). Frisvold and Konyar (2012) call this a "rationing model" (see Paragraph 2.4).

2.3.2 Normative versus positive models and the calibration issue

Normative models

The perspective and philosophy behind normative and positive models differ completely, in theory at least. The normative perspective which is a deductive approach assumes an *apriori* objective function and derives the optimality conditions . The aim of the model is not to represent the *real observed* situation but to represent the *optimal* situation. The interpretation of the difference between model and observed result is the sub-optimal character of the real observed situation. The modeled output is the "optimal" allocation of inputs.

This perspective appears to be relevant in exploring optimal water management solutions such as those discussed in Paragraph 2.2.6. The various model outcomes can be compared with each other even if the baseline differs from the real observed situation. An example of a normative linear programming model is provided by Doppler et al. (2002) who explore the improvement potential of farming in relation to water allocation on crops, together with the impact of water pricing strategies.

The limit of this approach is when significant costs or benefits are unobserved or unknown, and are not accounted for in the model. This can be the case with non-market costs such as leisure time for the farmer or unobserved rents such as those provided by contracts between farmers' and industry for specialty crops. In this case the model does not account for all costs and benefits and the optimal picture it provides is erroneous. The implication for calibration is that normative models are not calibrated: in consequence they do not replicate the observed situation. In practice these models specify linear costs and yields (Leontief technologies) and are referred to as linear programming (LP) models.

Calibrated linear programming models

Methods have been developed to calibrate LP models to observed allocations, although not perfectly. Accordingly, LP should not be systematically defined as a pure normative approach. A first method consists of a micro-approach in the sense that a deep understanding of the technical and economic processes at farm level is required. In this case all constraints related to the technical realities of farming (rotation, animal turnover, regulation etc.) are specified and should enable a closer approach to the observed situation. Another approach consists of increasing the degrees of freedom in the model specifications, to allow for partial calibration. In practice this can be done by integrating risk into the objective function which then becomes an expected profit function. This can be carried out via the MOTAD approach (Minimization of Total Absolute Deviation, Hazell and Norton (1986)) which calibrates the risk aversion parameter to minimize the discrepancy between modeled baseline and the observed situation. The risk aversion coefficient can be interpreted as a pass-through coefficient affecting utility according to the perception of variability from the farmers' point of view. Another solution is to build on multi-attribute utility theory and specify an objective function as the sum of weighted attributes: the weights can serve as calibration parameters, while minimizing the departure of the model from the observed allocation (Bartolini et al., 2007). However, the calibration of these models cannot be exact. Dono et al. (2010) recommend using the Finger and Kreinin similarity index (Finger and Kreinin, 1979) to evaluate the effectiveness of calibration. Recent applications involving water management in agriculture include Bazzani et al. (2004); Bartolini et al. (2007); Graveline et al. (2009); Acs et al. (2010); Graveline et al. (2012).

A major criticism is that LP often provides over-specialized responses (Gohin and Chantreuil, 1999), because crops that have the highest gross margins will be chosen at the maximum level until a constraint becomes binding and prevents the best crop from increasing further. Its inability to represent smooth reactions to policy shocks ("jumpy behaviour"), thus becoming too far removed from reality at least in the short term, is sometimes mentioned. This has been overcome by using regression to smooth the step inverse demand function (Booker and Colby, 1995). In medium-term simulations, "jumpy behaviour" is not a problem, because dynamics are not considered. Another disadvantage is the need of a large quantity of data at the farm level. The problem of imperfect calibration is however a minor issue when comparing policy alternatives, as long as as the model is a good representation of the farmer’s behaviour. It seems less suited for modeling detailed adaptations of farming in terms of input allocation (of water or nitrogen).

The LP cross-mix approach was developed by McCarl (1982) to avoid the overspecialization problem (See Appendix 1 for details). An example that focuses on agricultural water use is Graveline et al. (2013). The principle is to add a constraint to the LP problem to ensure a convex combination of historical crop mixes. By doing so, this constraint prevents unrealistic crop mixes, thereby implicitly accounting for crop rotation and other practices that affect crop choice. However, the main problem is that this specification can be viewed as overly constraining and the drawback of this type of model is that it can not simulate allocations that have not been observed in the past. This is a major problem when dealing with water use and resources, since tendencies such as climate change and requirements for reducing agriucltural water use in response to other (environmental and urban) increases in demand have created a totally new regulatory and natural environment. In addition, the context of high price volatility observed in recent years (Persillet, 2009) makes the economic environment completely new as well. However, Chen and Önal (2012) circumvent this problem by adding to the bundle of likely crop mixes certain, new synthetic crop mixes that are simulated with the help of supply-price elasticities and varied commodity prices.

Positive mathematical programming models

The *Positive* approach refers to inferring the behaviour of farms or of an aggregated region from observed data using econometric techniques. PMP is an intermediate approach between economic programming (deductive approach) and econometrics (inductive approach). However, it is still a programming approach. The seminal paper of Howitt (1995a) on Positive Mathematical Programming, has formalized the approach in the context of agricultural supply modeling. The principle of PMP is calibration of the crop specific model [1.1] to observed data by introducing non-linear costs or yields and, in some cases, adding unobserved costs to exactly replicate the baseline situation. It was characterized by Howitt (1995b) in these words: *"The PMP approach is developed for the majority of modelers who, for lack of an empirical justification, data availability, or cost, find that the empirical constraint set does not reproduce the base-year results."*

Allowing for more degrees of freedom in the objective function, the non-linear forms with concavity enable perfect calibration. The basic PMP problem is under-determined and as such has no unique solution. Consequently, several alternative calibrations were proposed by Heckelei (2002); Heckelei and Wolff (2003); Röhm and Dabbert (2003); Frahan et al. (2007); Howitt et al. (2010); Mérel et al. (2011); Mérel et al. (2013)). The trend is to use extra information, often supply elasticities, (Helming et al., 2001; Mérel et al., 2011) to improve model behaviour and reduce arbitrary specifications. Paris and Howitt (1998) use an entropy criterion. The initial solution to the under-determination of the problem was a simple ad hoc procedure that set certain parameters a priori (Howitt, 1995b). All specifications maintain concavity of the production function. The PMP method has been adopted by a significant number of authors involved in agricultural water use research. There is no prevailing form: some have adopted linear yields with non-linear costs, others non-linear yields with linear costs and still others non-linear yields and costs. Mérel et al. (2011) show for instance that the generalized Constant Elasticity of Substitution (CES) with a linear cost model is more flexible, less under-determined, and enables the calibration of larger sets of supply elasticities than the quadratic model. It is thus more appropriate for positive mathematical programming. Heckelei et al. (2012) discuss the state of the art of PMP models together with the remaining challenges, which are often analytically and computationally complex. We provide further details of some of the PMP models in Appendix 2.

One of the most common interpretations of non-linearity is that it readily accommodates the representation of heterogeneities in production factors such as soil quality, climate, managerial ability, rotation effects, etc. within a region.[6] In the CES or quadratic yield model which requires additional adjustment-cost terms (see Mérel et al. (2011)) the rationale is that costs are not necessarily observed. Other authors (Cortignani and Severini, 2009; Petsakos and Rozakis, 2011) use the argument of farmers' risk aversion to add non-linear terms in the objective function (see section on risk).

Implementation considerations

PMP calibration allows for automatic calibration that is time saving when compared to more traditional LP where the analyst has to characterize constraints and adjust them to get closer to the observed situation. This problem is exacerbated because traditional LP modeling has often been carried out at the farm scale for typical farms, and the calibration exercise has to be multiplied by the number of farm types, whereas PMP is often applied to entire regions. The self-calibrating PMP model may also be viewed as easier to replicate.

Validation of models by ex-post experiments

In all natural or physical sciences, models are validated after calibration. Validation may be defined as running the calibrated model with parameters corresponding to a real past situation different from the calibration period, and comparing the simulation results with the observed situation. In agricultural economics the studies which contain any validation of their models are rare. However, some examples exist: Heckelei and Britz (2000) validate their maximum entropy - PMP cross-section model and Blanco et al. (2008) design ex-post experiments to discuss three different types of calibration which may or may not consider the possibility of new crops from neighboring regions (within the modeled area). They consider observed cropping allocations before and after the 2003 CAP reform for an irrigation area in Italy. Gocht (2005) also evaluates a number of existing PMP variants with ex-post experiments in Germany. Kanellopoulos et al. (2010) compare two PMP variants with regard to their forecasting capacity and compare simulated results with observed acreage allocations, and, thereby provide validation for their models. They point out that other economic and environmental variables could be considered for validation, depending on the policy questions involved (nitrates, profits etc.).

[6] even if this is not often mentioned or discussed by authors, according to Heckelei et al. (2012)

2.3.3 The time dimension

From a social planner's perspective, time is central to the *water mining* optimization problem *(What is the optimal allocation of water over time?)*, e.g., Provencher and Burt (1994). This problem is common to the management of all natural resources (biodiversity, fishing, etc.) that can be viewed as a flow of services provided by stocks of natural capital. However, the viewpoint of WPM is often different, since it aims to represent the behaviour of farming instead of social optimality.

The time dimension is central in the scarce-resource allocation problems that can be formalized by WPM, because both resources and demands are variable over time. The resource availability variation can be viewed as deterministic or stochastic when uncertainty is attached to it; in reality this is always the case. When this issue is important, economic models are often connected with hydro(geo)logical models to account for the evolution of resources: conversely, the hydro(geo)logical model can account for agricultural water withdrawal in its balance. The interaction of models can then be observed over multiple periods to explore their joint evolution. A second point is the timing of the water demand at both the intra-annual and inter-annual levels.[7] However, even if the water withdrawal is not constant over time, the respective decisions do not occur at the same time, but can be compared to discrete decisions. Modeling the tactical choices when the cropping pattern is already fixed (short-term, intra-annual) is different from modeling the strategic choices such as irrigation investment (over multiple years) and/or cropping pattern decisions (multiple years for perennials or annual for annual crops). However, the majority of agricultural water-demand PMs do not consider the dynamic dimension of the water demand and focus on a single period optimization (agricultural campaign year). A third reason for considering dynamics is that it can be an interesting way to represent the adoption of agro-environmental measures that will affect input use (see for instance Schader et al. (2008), who focus on diffuse pollution, but this approach could equally be applied to water-saving measures).

Two types of specification for these dynamic problems can be distinguished. The first, *recursive modeling* (Day, 1963), maintains a single-period optimization; the second *intertemporal modeling*, optimizes an objective function over several periods. In recursive modeling the state variable produced at stage $n-1$ is used at stage n, but each state has its specific optimization. The expression including the control variable and linking state $n-1$ and n is

[7] This choice should also depend on the characteristics of the water resource concerned (*Is withdrawing 1 cubic meter in April from the resource equivalent to withdrawing it in August ?*).

called an equation of motion.[8] The solving of such problems is the same as a classical static optimization problem (linear or non-linear problems). Inter-temporal models maximize the objective function (profit or utility) over multiple periods of time accounting for a discount rate. Inter-temporal models are also often recursive and include an equation of motion. Few dynamic models have been applied to agricultural water-management issues, although concrete cases can often be formalized as dynamic problems. One of the reasons might be the intractability of the problems. In practice, dynamic optimization problems can be solved by various techniques, but the solving is often complex. The level of complexity depends on the number of variables. To solve these problems analytically, several solutions exist. A frequently used method is optimal control theory. The paper by Blanco Fonseca and Flichman (2002) offers an overview of the different techniques available to resolve such problems. One example is Ding and Peterson (2012) who apply a dynamic three-stage nested optimization model. The model optimizes step by step, the irrigation technology choice, the optimal cropping pattern and the water use.

If uncertainty that may influence output is significant after the first decisions have been taken and information arrives before other decisions are taken, the Discrete Stochastic Programming (DSP) approach can be utilized. This model is often applied in multi-periodic problem settings related to agricultural water use. We disucss this approach further in paragraph 2.5.3.

2.4 Incorporating water into the production functions

At the regional agricultural level, inputs - water and nitrogen - are not allocated in fixed proportion to land, i.e., their level of use may vary, land being fixed, because there can be substitution between inputs: this characteristic allows "intensive adjustments", i.e., applying less or more water per hectare of crop, when changes occur. All models that are aimed at accurately representing the impact of input (water/nitrogen) scarcity and related policies on agriculture should ideally capture these adjustments, which represent, along with extensive margin adjustments,[9] opportunities for the farming system to absorb shocks. Ignoring this will lead to overestimation of the economic impact of reduced resource availability and will bias measures of the cost-effectiveness of available policy options - potentially

[8]For instance, the total water use by farming at a given point is used in the calculation of the water resource state variable at $n+1$ (piezometric height for instance), but the optimization is performed each year (i.e. a static optimization).

[9]adjustments that involve land/cropping pattern changes and that imply changes in input use

leading to poor decision-making (Frisvold and Konyar, 2012). Output effects may also be affected. For instance, assuming that crop-water intensities are fixed could lead to overestimating the decrease in irrigated acreage, and, to the extent that irrigated crops have higher yields than rain-fed crops, the associated decrease in agricultural output will also be over-estimated. This is why incorporating the responses of yields to inputs (water/nitrogen) appears necessary.

2.4.1 Response of agronomic yield to inputs

To incorporate the effects of varying levels of input application on yields, agronomic information is required (see for instance Godard et al. (2008)). The data used to characterize this relationship are experimental field data or simulation results from agronomic crop growth models. The relation between yields and inputs such as water and nitrogen is non-linear. Considering a wide range of nutrient applications, Lanzer and Paris (1981) draw a curve that is first convex, then concave, then plateau and then decreasing. This "saturation" effect is explained for exceeding nitrogen application which induces lodging. Similarly, water in excess ends by affecting crop growth owing to a lack of aeration in the root zone. The concave property before reaching y_{max} seems largely accepted for both water and nutrient (Barrett and Skogerboe, 1980; Lanzer and Paris, 1981; Godard et al., 2008). Zhang and Oweis (1999) found the quadratic formulation to be suitable for representing the relationship between irrigation water and yields for wheat.

Since the 1970s, agronomics has developed relations that link yield to evapotranspiration (ET). The most commonly used form is the "FAO" form (Allen et al., 1998):

$$y_i = y_{imax} * (1 - k_i \left(1 - \frac{ETA}{ETC}\right))$$

where y_{max} is the maximum yield potential (with no water stress), k_i the crop yield response factor of crop i and ETA and ETC respectively the actual and potential evapotranspiration determined by radiation, temperature, humidity, wind speed etc. An alternative form that accounts for differing growth stages (t) is Jensens' form (Jensen, 1968):

$$y_i = y_{imax} * \prod_t \left(1 - \frac{ETA_t}{ETC_t}\right)^{\lambda_t}$$

where λ_t is the specific t stage exponents such that $\sum_t \lambda_t = 1$. Rao et al. (1988) also describe an agronomic function achieved by summing or multiplying n crop growth stages.[10]

Note also that these functions reflect a reasoning in terms of yield potential, i.e., the maximum yield that can be reached when growing a crop, and envision a function that is defined on $[0; Y_{max}]$. Conversely, economists need functions that are differentiable (for first order condition calibrations) and are thus defined on values above y_{max}.

Connor et al. (2012) further describes the impact of water on yields for perennial crops by adding a minimum threshold level for the water applied under which the yield is also affected in coming years, with the help of a “penalty yield". Other forms that directly link the irrigation level and the yield have been used by Mérel et al. (2013) as follows:

$$y_i(w_i) = \frac{a_i}{1 + \exp\left(-\frac{w_i - w_{i0}}{b_i}\right)}$$

where the unknown parameters are a_i, b_i and w_{i0}, w_i denotes water intensity, $w_i = x_{i2}/x_{i1}$ and y_i is yield. This functional form is flexible enough to allow for a sigmoidal response to water with a horizontal asymptote for large irrigation values. Note however, that they are not directly incorporated into the model.

2.4.2 Incorporation into the economic models

The economic model should represent the perception and knowledge of the farmers production function and not necessarily the real production function. If agronomic functions are incorporated into economic models, we assume that farmers have a perfect knowledge of crop growth. This assumption might be acceptable in the majority of cases, but perhaps not in cases where new crops are adopted. It might explain why economic models rarely use the very detailed multiple-stage agronomic functions as presented in the preceding paragraphs. As a consequence, one of the challenges is to fit a function that links yields to applied irrigation water that satisfies often different soil conditions, that incorporates time (often one year), and other environmental factors (no explicit consideration of parameters that define the evapotranspiration). The incorporation of this agronomic information/behaviour varies substantially depending on the economic model. We discuss the various approaches in the following paragraphs.

[10]These formulations should be used to express the relationship $\frac{y_i}{y_{imax}}$ but preferably not for the absolute value, which is highly dependent on local factors.

Discrete point incorporation

The first solution is the incorporation of a discrete set of activities corresponding to different levels of input application (Taylor and Young, 1995; Bazzani, 2005; Cortignani and Severini, 2009; Graveline et al., 2012). This consists of multiplying the number of activities, i.e. crops i, without incorporating a function into the model that depends on water. As such the various activities represent the agronomic response to inputs but the objective and production functions do not. This solution is adequate when the model is linear and can be considered as a linearization of the non-linear relationship between water/nitrogen and yield.

A similar approach was adopted by Medellín-Azuara et al. (2010) who incorporated a yield parameter y, which takes varying values depending on the scenario, e.g. climatic change).

Incorporation of a production function into the economic model

Other solutions build on the fact that programming models can accommodate detailed production functions, in this case they must represent the non-linearity of yields with varying levels of water or nitrogen. However, the economic production function in PM must satisfy certain conditions in order to be tractable and can not necessarily take over the agronomic input-yield response functions. They must be concave (marginally decreasing returns) and strictly increasing (see Beattie et al. (1985)), thus excluding the agronomic plateau and the decrease of y after y_{max}.

Formalization of the relationship between water quantity (x_{i2}) and yield (y_i) has been addressed mainly via two functional forms in economic programming models.[11] The first is the quadratic form, in this case, it specifies fixed proportions in land (x_{i1}) and quadratic returns in water. A similar function quadratic in nitrogen input could also be specified.

$$q_i = x_i(\alpha_1 + \alpha_2 x_{i2} - \alpha_3 x_{i2}^2) \tag{2.1}$$

Figure 2.1 illustrates the behaviour of this function.

This form is used by Cai and Wang (2006) and Connor et al. (2009). It was also used in a previous version of the Californian SWAP model (Howitt et al., 2001). The rationale

[11] These forms can accomodate more than two inputs (land and water here)

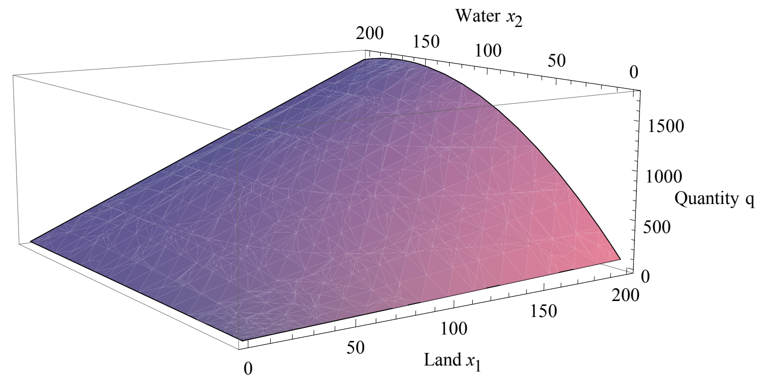


Figure 2.1: Quadratic production function with two inputs (land & water), with land in fixed proportion with quantity

for choosing this form has not been reported from a theoretical point of view but it accommodates observations of yield behaviour with varying water levels first increasing and then decreasing after a threshold. However it does not fit the agronomic plateau. Knapp and Schwabe (2008) further argue that in the case of two inputs (nitrogen and water) it allows for too much substitution and input use. This quadratic form has been made more complex by Connor et al. (2009) for perennial crops to account for low threshold levels of water application under which the yields in later years will also be affected because of plant damage.

The second form is the Constant Elasticity of Substitution (CES) form. The elasticity of substitution ($\sigma_i = \rho_i/(\rho_i - 1)$) is the proportional rate of change of the input ratio divided by the proportional rate of change in the rate of technical substitution (Beattie et al., 1985). As such it is a measure of the substitution level of two inputs (an elasticity of 0 is equivalent to the fixed proportion case and an infinite elasticity indicates perfect substitutes).[12]

$$q_i = \alpha_i \left(\beta_{i1} x_{i1}^{\rho_i} + \beta_{i2} x_{i2}^{\rho_i}\right)^{\frac{\delta_i}{\rho_i}} \tag{2.2}$$

with $\beta_{i1} + \beta_{i2} = 1$ parameters and δ_i the returns to scale parameters. The first form used were non generalized forms with $\delta = 1$ (Howitt, 1995b) resulting in constant marginal returns. In this case quadratic cost terms have to be added in the objective function to satisfy strict concavity.

[12]The Cobb-Douglas function often used in economics, which is a particular case of the CES function for $\rho \to 0$ is, to the best of our knowledge, never used in PM.

Figure 2.2 illustrates the behaviour of a CES function with constant return to scale and Figure 2.3 displays a CES function with decreasing marginal returns ($\delta_i < 1$).

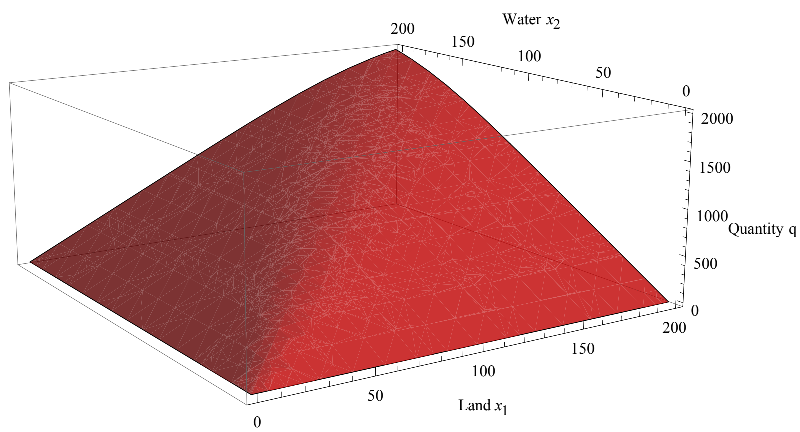


Figure 2.2: Constant Elasticity of Substitution and constant returns to scale ($\delta = 1$) production function with two inputs (land & water)

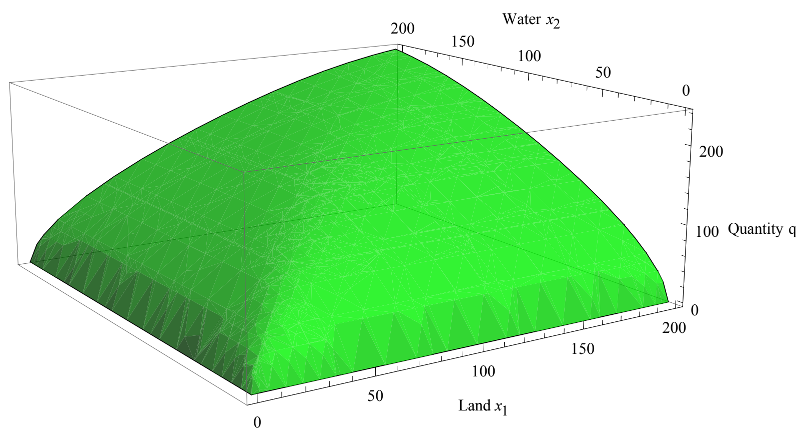


Figure 2.3: Constant Elasticity of Substitution with decreasing returns to scale ($\delta = 0.6$) production function with two inputs (land & water)

This form has been employed by fewer authors in PM models. However, its main advantage is to allow for limited substitution among different inputs and it can accommodate decreasing marginal returns (for $\delta < 1$). The main "agronomic" advantage over the quadratic production function is that it is closer to a plateau form for higher values of input use as the CES approaches an asymptote. Conversely, the CES does not decrease after a certain threshold, and this property would be interesting for representing the "saturation" effect, as discussed earlier.

The majority of PM approaches use data obtained from crop model simulation (Mérel et al. (2013) use DAYCENT; García-Vila and Fereres (2012) use the Aquacrop FAO model). Parameters are then estimated from regressions.[13]

Some authors have recently multiplied the number of inputs (x_j) considered in the yield function by accounting for water and salts (Booker and Young, 1994; Connor et al., 2012) or water and nitrogen (Knapp and Schwabe, 2008).[14]

As remarked by Mérel et al. (2013) the majority of authors incorporate the possibility of varying levels of water intensity by capturing nonlinear biophysical processes affecting crop yields in otherwise linear objective function programming i.e. considering yields fixed to the land (constant return to scale). This is the case for the models developed by Dinar et al. (1991); Weinberg and Kling (1996); Posnikoff and Knapp (1996); Connor et al. (2009). Others, based on the principles of positive mathematical programming (PMP) models of regional supply that allow for input substitution (Howitt, 1995a; Medellín-Azuara et al., 2010; Mérel et al., 2011; Frisvold and Konyar, 2012) use a production function having the form of a Constant Elasticity of Substitution. Some of these models assume that yields are decreasing with acreage planted owing for instance to land heterogeneity or rotational effects.

For instance, Maneta et al. (2009) incorporate both a CES production function with more than ten inputs including six for irrigation : surface and groundwater, hired and family labor, capital and electricity) with the same elasticity of substitution and a quadratic term in the cost function. Medellìn-Azuara et al. (2009) also employ a CES function with five inputs land, labour, water, supplies, and machinery. The reliability of such complex models might be questioned, because they assume the same substitution among very different types of inputs (land, labor, irrigation, capital etc.). Nested CES functions are a solution for specifying different substitution elasticities for different inputs (Frisvold and Konyar, 2012; Medellin-Azuara et al., 2012). Howitt et al. (2010) and Medellin-Azuara et al. (2012) also assume substitution between water and capital investments in irrigation efficiency. Another problem with using CES functions is the relative scarcity of data on substitution elasticities between water and land. Table 2.1 assembles the values that we found in PM and shows the relative heterogeneities among authors. They may represent the differences that characterize

[13] This practice is not limited to programming models: see for example Garrido (2000) who uses EPIC model simulation data to fit a yield response curve to water and nitrogen, which is used to determine a semi-logarithmic water demand function

[14] Connor et al. (2009) discuss the desirability of incorporating CO2 concentration in air on yields, but argue that this effect is negligible.

Author	Inputs	Case study	σ	Source
Howitt et al. (2012)	W& labor	California	0.17	justifies limited substitution
Graveline and Mérel (2013)	W&L	France (Beauce)	0.05-0.25	Calzadilla et al. (2011)
Medellín-Azuara et al. (2010)	W, L , labor, supplies, machinery	Mexico	0.25	-
Howitt et al. (2010)	W, L labor & supplies	California	0.22	-
Mérel et al. (2011)	W&Ł	California	0.5	-
Medellin-Azuara et al. (2012)	W& capital on irrigation technology	California	0.5 to 0.9	Hatchett (1997)
Howitt (1995b)	W, L, capital and chemicals	USA	0.7	-
Chatterjee et al. (1998)	W&L	California	0.7	Hatchett (1997)

Table 2.1: Values of input elasticity of substitution encountered in CES models. W& L stands for Water & Land

the case studies, but may also reflect a limited availability of regional and crop-specific data. The values range from 0.05 to 0.9.

2.4.3 Calibration of implied model response to agronomic data

A further step towards improving model behaviour is to calibrate the model's implied response against agronomic, i.e., biophysical data on yields as first suggested by Mérel et al. (2013). The idea is to replicate, near the reference, the yield response to input variations i.e. to calibrate the CES model against observed-agronomic input/yield response curves. Technically this is made possible by fitting the agronomic yield elasticity to water with the implied yield elasticity of a CES -decreasing return to scale- model. Mérel et al. (2013) first fit a predetermined functional form to agronomic data and then recover the yield elasticity at the observed point.[15] This is made possible by adding an extra PMP adjustment cost term (increasing the number of degrees of freedom in the problem) to any of the inputs for which the agronomic response is calibrated. Yield elasticities $((dy_i.w_i)/(y_i.dw_i))$ can be recovered from agronomic data. Frisvold and Konyar (2011) report values used in the USARM model that are relatively low and crop specific, they range from 0.01 to 0.14.

[15]Note that the functional form is different from the quadratic form and is : $y_i(w_i) = \frac{a_i}{1+\exp\left(-\frac{w_i - w_{i0}}{b_i}\right)}$ as described in paragraph 2.4.1

However, the main limit is that calibration is carried out on the reference situation even though yield elasticities are not constant in input use. Graveline and Mérel (2013) provide an application to Beauce.

The CES model could also be calibrated using the regional, crop-specific agronomic production function alone, if available, instead of using supply elasticities. This method is used in cases where new crops (having no existing economic references) need to be calibrated. The example for this is Mérel et al. (2012) who calibrate a switchgrass production function for California based on agronomic model results for a large number of geographic conditions (cells) in California. In theory, all crop production function could be calibrated in this way. From this example, it appears that this calibration method yields higher implied supply elasticities than the supply elasticities in the literature.

2.5 Uncertainty and risk

The difference between *risk* and *uncertainty* is that *uncertainty* refers to imperfect knowledge while *risk* refers to uncertain consequences. Another definition associates *risk* with something that can be characterized with probabilities whereas *uncertainty* can not, i.e., probabilities are unknown.

2.5.1 Why introduce risk and uncertainty into WPM?

Considering uncertainty and risk when representing water demand is relevant because of the uncertain nature of water related variables, particularly the water availability for irrigation and the yields resulting from climatic conditions. Indeed both water resources and water requirements by crops and consequently input use or yields can be subject to significant uncertainties, which farmers might consider in their decisions; other risks such as price related ones may also be considered. Another rationale for considering uncertainty is that irrigation can be considered as a way to reduce risk. The *expected utility theory* has been applied to the developments on risk and uncertainty in agricultural economics and on PM. It states that if the preferences of a decision maker satisfy the independence and continuity axioms, they can be represented by an expected utility function which is also called a *Von Neumann and Morgenstern* utility form (Mas-Colell et al., 1995).

Irrigated farming is sometimes modeled based on expected utility theory, thus incorporating risk into the objective function (Arriaza and Gòmez-Limon, 2003; Finger, 2012; Graveline et al., 2012). We should note that these studies all model farms and not regions. This can be explained by the fact that uncertainty might be lower at regional scale than at farm scale. However, if farmers all account for risk and have a risk-averse behaviour, this should also be the case at an aggregate level.

Risk or uncertainty can be specified in the objective function, i.e in prices, yields and revenues, or in constraints, to represent stochastic resource availabilities. Both are practiced and relevant to study topics related to water management.

Two main approaches are distinguished in the following two paragraphs: (i) those that account for risk in the objective function or in the constraints and (ii) those that allow for recourse in the decision. In this last case, information that arrives at a later stage may reduce or suppress uncertainty that existed in an earlier stage (for instance information about water availability arrives after a first stage where the decision on crop allocation to land has already been taken).

The mean-variance and the MOTAD model which incorporate risk are presented in Appendix 3. Note that some of the differing models can be combined, see for instance Paris and Easter (1985) who combine mean-variance and chance programming.

2.5.2 Stochastic programming

WPM that specify expected profit functions are mainly linear, e.g., Arriaza and Gòmez-Limon (2003); Graveline et al. (2012). Incorporating risk has two main advantages in WPM. The first is to account for stochastic variables such as yields or water resource availability in order to better represent the relationship between production and water use and resources. The second is a technical advantage: the inclusion of risk, in, for instance, the MOTAD[16] specification (Hazell and Norton, 1986) permits one more degree of freedom which is convenient for calibration as already discussed in Paragraph 2.3.2.

Arriaza and Gòmez-Limon (2003) show, based on a review, that in classical agricultural supply modeling there is no evidence of a systematically better performance of risk models over deterministic models. However, their study finds that an additive utility function with maximization of total gross margin and minimization of total qualitative risk outperforms deterministic modeling (among other Positive Mathematical Programming). This

[16]As argued by McCarl and Spreen (1997) the MOTAD model does not have a direct relationship to a theoretical utility function. As such an interpretation using the classic Arrow Pratt coefficient of absolute risk aversion (r_a) is not possible; $r_a = -U(x)''/U(x)'$, with U being the utility. For a linear model, the case with MOTAD, we would have $U''(x) = 0$ and this means risk neutrality.

experiment was carried out on the impact of the 1992 CAP reform on irrigated farms in Spain.

A methodology has been proposed recently by Petsakos and Rozakis (2011) to account for risk in the objective function with a PMP model, but to our knowledge there have been no studies that incorporate water as an explicit input. The general idea is to combine the expected utility theory with the PMP parameter calibration procedure. In this example a logarithmic utility function is used, since it has the advantage of being concave. The economic interpretation of the model is that the implicit information recovered through dual values of the calibration constraint can reveal the farmer's profit expectations and risk attitude. A variance-covariance matrix is obtained using a maximum entropy specification (Golan et al., 1996).

2.5.3 Discrete Stochastic programming (DSP)

> *"The nature of this type of problem typically requires the allocation over time of limited supplies of resources among alternative production activities, where resource supplies, input-output coefficients, factor costs, and product prices may not be known with certainty at the various allocation dates."* Rae (1971b)

DSP is also referred to as *Stochastic programming with recourse*. The problem is decomposed into several decision stages (often two) in which new information is available in stage: this can be represented by decision trees. The typical case treated with DSP is cropping pattern planning under weather/water uncertainty. In the first stage, cropping patterns are decided and crops are sown; in a second stage, when weather events occur some decisions, for instance one relating to irrigation intensity, are revised. The main difference from the precedent modeling method is that the decision maker has recourse after some of the uncertainty disappears.

Generalized by Rae (1971b) DSP has been applied by a number of authors (Rae, 1971a; McCarl et al., 1999; Mejías et al., 2004; Calatrava and Garrido, 2005; Connor et al., 2009; Dono et al., 2010, 2013); the majority use DSP to account for uncertainty about water availability, e.g. precipitation, or water requirements by crops. Different stages correspond to different periods of the year.[17] McCarl et al. (1999); Mejías et al. (2004); Connor et al. (2009) define

[17] However the different outcomes for the states of nature considered have to be feasible. Chance constrained programming or goal programming accommodates cases were feasibility cannot be assured (Hazell and Norton, 1986)

a first stage which models the choice of long-term capital investments that remain fixed for a number of years regardless of annual stochastic variations in water allocation and water price. The second stage models short-term (annual) decisions concerning water application rates and acreage fallowed. These short-term decisions are conditional on the capital level chosen in the first stage. Considering the need to account for the irrigation investment in the objective function seems to be a relevant choice when the area considered faces new irrigation opportunities. This might be due, for instance, to a new water infrastructure or if new irrigation technologies became available to farmers or irrigation associations, e.g., drip or sprinkler irrigation in areas where gravity irrigation is practiced. Iglesias et al. (2007) derive a drought-management index from the optimality conditions of a discrete stochastic programming model for an application to reservoir management under water stock risk. Krautkraemer et al. (1992) suggest the incorporation of different risk aversion coefficient into DSP distinguishing between intra-year and inter-year risks.

In the model specification, a set of constraints link the various periods with each other. Varying numbers of time periods can be modeled, but multiplying the number of periods also strongly increases the data requirements and the tractability of problems.

2.6 Spatial modeling scales and the aggregation bias

The spatial scale at which optimization is practiced determines model behaviour. To illustrate this, assume a water resource available to farm A, if the optimization is realized at farm scale, then the model will allocate water among land available to farm A so as to maximize utility. If the optimization level is regional than this same water endowment might be allocated to other farms, i.e., to lands that are more productive. As such the choice of the modeling scale is determining for the model's behaviour. However, the choice of model scales is rarely discussed.

2.6.1 Farm scale

In the majority of countries where farmers are free to grow whatever they wish, the decision scale is the company's i.e. the farm's and decisions are taken according to its various assets (human, financial, social). Depending on the production system this assumption can be modified when farmers grow contract crops (for instance biofuels or sugar beet) and will depend, at least in part on the agro-industry that does or does not provide them with a contract. But in the end the farmer will still decide what to grow, in light of all the resources he possesses (contracts or quotas included).

The modeling scale should also be chosen according to the homogeneity of inputs and constraints over the entire region considered. Consider the example of the water resource constraint. If farms face different constraints on water in an upstream-downstream scheme, with upstream users having more water availability then downstream ones, differentiating between farms is important. Thus the modeling scale should be the farm scale.

In consequence the farm scale seems to be the appropriate level for representing the system and has been adopted by many authors (Gòmez-Limón and Riesgo, 2004; Bazzani, 2005; Bartolini et al., 2007; Garrido, 2000; Finger, 2012; Lehmann et al., 2013). In practice, it is not possible to represent all the individual farms in a model to represent a region. This is mainly because of lack of data or owing to computational or time constraints. However this is no longer the case with self-calibrating models such as PMP. It has been overcome by modeling typical farms from farm typologies. These consist in grouping farms into types that have a number of common properties (for instance size of arable area on the farm, the farm's diversification level, types of major activities (see for example Köbrich et al. (2003)). This practice induces an aggregation bias, which is limited when the typology has been well defined, i.e., when discrepancy between the real farms and the type is low. An advantage of farm-scale modeling is the ability to interpret the results in terms of equity and to address distribution effects.

2.6.2 Regional scale

There are two main reasons for considering the regional scale. The first is in order to explore the social optimum of a region, because regional-scale optimization allows for variable allocations of resources among farms. This optimization has no reason to correspond to the observed real situation and is a truly normative approach. The second reason applies when sufficient homogeneity is observed across the region and we can view the region as a large farm, e.g. Judez et al. (2002). An additional reason would be when the regional scale is more of a default option. This applies when no data exist at farm scale or there are no means for constructing farm typologies or making inquiries.

Increasing number of authors are adopting regional-scale modeling (Taylor and Young, 1995; Sunding et al., 2002; Iglesias-Martinez and Blanco-Fonseca, 2008; Balali et al., 2011; Ejaz Qureshi et al., 2013b), mainly to reduce the need for data and to ensure the quality of data they employ. The necessary assumption is that farming has reached an equilibrium, and that if an input might be better used by another existing technology or producer in the region, it will be allotted to that technology or producer. In other words, regional modeling makes the assumption of fluidity of inputs throughout the whole region. This is a strong assumption, and will be more or less acceptable depending on the agricultural region and its size.

In the case of a groundwater resource, with multiple/individual farms accessing to the resource, the modeling scale can be the regional one, i.e., it should be defined as the hydrogeological unity. The main limit of regional modeling seems to be the high level of aggregation, which assumes a homogeneity of resources and assets, that is rarely the case in real-world settings.

In summary, the scale considered should be as small as the assumption of homogeneity of resources and constraint permits.

2.6.3 Spatial upscaling and downscaling

Although regional modeling is often more convenient than farm-scale modeling, the farm level is the locus of specific constraints, e.g. water availability, and is critical to policy analysis, such as the distributional effects of income. In addition having a more detailed spatial resolution is also relevant in some cases of water resources impact assessment as well as for various environmental issues (Chakir, 2009). For instance, depending on the soil, sub-soil and aquifer characteristics the nitrogen impact of a given crop-technology may be different if it is located at different places on an aquifer. In such cases, downscaling of the simulation i.e. spatialization of the results from regional modeling may be necessary and could lead to differing environmental impacts.

Howitt and Reynaud (2003) suggest a method for downscaling regional modeling results to smaller areas (districts in California) using maximum entropy. Gocht and Britz (2010) provide a Bayesian framework for downscaling of regional model results to farm level in order to assess local policy impacts. Chakir (2009) suggests a downscaling approach that builds on disaggregated biophysical data and aggregate economic data using a generalized cross-entropy approach.

However, downscaling approaches do not account for farm-scale constraints, farm- specific resources or technologies and consequently for structural changes at the farm level. Farm-level models can accommodate some of these requirements, which makes them more desirable in certain settings and policy perspectives. However, they also do not accommodate the specific differences within farm-types (including social or cultural characteristics) that make choices different from one farmer to another even when they have the same broad economic characteristics.

2.7 Conclusion and research agenda

Our review has shown that a majority of WPM are developed to support the analysis and exploration of the impacts of water policy instruments. One of the main reasons that mathematical programming accommodates the analysis of issues related to water or nitrogen management is that it specifies crop-specific production functions that directly relate inputs such as water and fertilizer to yield, i.e., production. This ensures that the analyst obtain a detailed understanding of the effects simulated by the models. Specifically, they allow us to envision the types of adaptations made under growing constraints. The adjustment possibilities can, in theory, be assessed by WPM. In practice, this depends on the flexibility of the model and its capacity to represent intensive margin adjustments, i.e., varying water application rates. The consequences of simulated scenarios in terms of profits and production are also among the model's results, also the shadow values[18] of water: this enables derivation of the water demand function. Most of the reviewed WPMs are steady-state models, implying that the analysts are more interested in the equilibrium itself then in the way the equilibrium is reached or evolves. They are sometimes connected with other models or methods to complete the evaluation, for instance, they can be coupled with bio-physical models or combined in a real-option setting. One of the main challenges of economic modeling for water demand modeling is finding the best trade-off between constraining the model sufficiently to represent the observed reality and allowing sufficient flexibility for the model to be able to simulate alternative situations.

The need to incorporate multiple policy concerns in models

Programming models have been used mainly for a single modeling purpose, traditionally to estimate supply responses to price and agricultural policy shocks. As shown in this review a diverse literature has responded to the challenge of modeling agricultural responses for the assessment of environmental policy impacts. More recently, under the Water Framework Directive, multi-objectives and issues have to be treated jointly to take into account their

[18] also called the marginal, opportunity or scarcity cost

combined effects on quantitative and qualitative water issues. If a given policy, say quantitative water management, has an impact on cropping patterns, it will also have a marginal impact upon nitrate pressure on water resources and, probably, on the Green House Gases (GHG) emissions from farming. Competition may also occur between environmental objectives and supply-oriented policies such as biofuel incentive policies, e.g., Graveline and Rinaudo (2007), who showed that the environmental and less liberal B2 SRES scenario might be counterproductive for obtaining nitrate improvement in groundwater, owing to an increase in biofuel crops.

Very few modeling studies have been developed within a multi-environmental issue framework (say water, air pollution & GHG and soil erosion). The FSSIM framework was developed as a generic bio-economic model to account for the diverse environmental externalities of farming (Louhichi et al., 2010), however these authors do not account for quantitative water use by farming. If they are to support future policy planning, these models should not be developed futher as lang as they focus on only a single environmental pressure, because the synergies or competition between sector policies (agricultural, air pollution & GHG, nitrate, pesticides, and quantitative water issues) also need to be accounted for. The purpose for which a single policy might still be simulated is to explore the marginal impact of a policy on the farming sector as such, for instance the adaptation of the farming sector to a reduction of water availability. However, known changes in other policies or input parameters, e.g., prices should be accounted for, in order to relate to a realistic medium-term baseline and to assess the marginal effect of a policy for a given baseline.

The challenge of modeling the adoption of practices and new technologies

Changes in the socio-economic and environmental contexts will lead farmers to adapt, and new crops and/or new technologies will be adopted, e.g., Louhichi et al. (2010).

The main problem facing the modeler is the limited availability of technical and economic information concerning the new activity (yield, input use, price etc.). Mérel et al. (2012) use agronomic information on new biofuel crops to recover the necessary parameters in their economic model and assess the adoption rate for this new crop. One of the technical challenges in this type of exercise will be to accommodate calibration of the model to the possibility of increasing volumes of agronomic or economic data. Another promising method for representing the adoption of new technologies or practices leading to reduced input use in a setting of uncertainty is real option theory, as discussed in 2.2.4.

Another important need is to characterize the ways in which farming adopts new practices and technologies based on real world observations. This requires the collection of empirical data and econometric analysis to assess how farming adapts to increasing constraints. This could be of use in refining the parameters of WPM, but could also be incorporated into other types of models such as macro-economic models.

Thus, a detailed understanding and representation of new activities, including environmental practices, such as organic farming and deficit irrigation, still seems to offer a broad field for research.

Far from the reference simulations

The programming models discussed here may not be valid for simulations that are remote from the reference conditions. LP models at the farm scale often work with farm typologies that might evolve with time (expansion of farms for instance, of evolution of technical constraints) and structural changes in typologies would require additionnal specifications to be included. PMP models are not suited to the simulation of major changes, because they are calibrated against first-order conditions. Chen and Önal (2012) discuss this issue for a particular LP model type, i.e., the crop-mix-approach. This issue of behaviour that is "far from the reference" model could be explored by simulation and comparison with observations, so as to check and improve the consistency of the overall model and its ability to simulate "far from the reference" policy experiments.

Appendix 1: The cross-mix approach: avoiding over-specialization

Alternative forms have been introduced to improve the calibration and replication of the reference situation, which is particularly problematic with LP. One of them called the "historical crop mix' and has been introduced by McCarl (1982). This approach consists in introducing an additional constraint that ensure the simulated crop mix is coherent with historical crop mixes, it is formalized as follows:

$$\gamma_i = \sum_{i \in I} \sum_{z \epsilon Z} \gamma_{iz} b_z \text{ subject to } \sum_z b_z = 1$$

This constraint assures a convex combination of historical crop mixes, where γ_i denotes current crop choice in area , γ_{iz} denotes the historical crop mix in year and b_z is a variable that denotes the share of each historical crop mix in the solution. It prevents the model from choosing crop mixes that lay beyond the boundaries of crop mixes that have been chosen in the past, thereby implicitly accounting for crop rotation and other practices that affect crop choice (McCarl, 1982).

The drawback of this approach is that a bias might occur, in the sense that the model is not capable of producing sensible crop choices when water availability (or some other model input) has a value outside the range of its historical levels.

Appendix 2: Non-linear, Positive Mathematical Programming models

The interest of non-linear models is to account for non-linearities in the production or cost function. Non-linearity is the mathematical way to represent heterogeneities of production factors for instance farm technology and capacity but also soil and climatic heterogeneity within a region. Heterogeneity is evident at regional scale where the variability among factors is more stringent than at the local/farm scale. At the farm scale linearity might be acceptable as described by Chen and Önal (2012) and adopted in a number of works until now as seen before. Nevertheless at regional scale the non-linear assumption appears necessary to avoid over-specialization, among other and represent better the reality. There is also a very interesting technical/mathematical property that argues for non-linear modeling. This choice enables better calibrating models to observed data, i.e. reality, because more parameters need to be calibrated and thus the problem to be solved has more degrees of freedom and this enables exact calibration. Since the first detailed formalization of PMP (Howitt, 1995b) a number of alternative forms have been developed according objectives and cases to be modeled.

All specifications maintain concavity of the production function.

The "classical" PMP Howitt form

> *"The PMP approach is developed for the majority of modelers who, for lack of an empirical justification, data availability, or cost, find that the empirical constraint set does not reproduce the base-year results'." (Howitt, 1995b)*

The word "positive" refers to the integration of observed behaviour information in the specification. The widely used form, since the PMP first formulation of (Howitt, 1995b) is the quadratic form. The interpretation of a non-linear term in the revenue / production term is that yields are marginally decreasing because of heterogeneity of land quality. As suggested initially by Howitt (1995a); Mérel et al. (2011); Mérel et al. (2013); Judez et al. (2002) work with this assumption of non-linearity in the revenue term. Howitt (1995a) justifies the choice of the supply non linearity because the yield data might be more available to modelers than cost data.

The non-linear term can also be in the cost term and correspond to a different interpretation of non linearities (yields are constant over land but cost a marginally increasing). The quadratic form (compared to other "power" forms) is always adopted. It is more a default choice and the simplest choice (Heckelei, 2002). Henseler et al. (2009) analyses this choice as being the simpler and thus in the line with the "philosophy of science". Medellín-Azuara et al. (2010) also suggest an alternative exponential cost function. Several authors (e.g. Heckelei and Wolff (2003); Heckelei and Britz (2005); Onate et al. (2007)) if not the majority, have used the **quadratic cost** specification which can be written in the following way:

$$c_i\left(x_i\right) = \alpha_{ij} x_i + \frac{1}{2} \beta_{ij} x_i^2$$

With α_{ij} and $beta_{ij}$ and x_i the land input for crop i.

The estimation of this model has been proposed by Howitt (1995a) in a two-step procedure.

- Step 1: the LP stage.

  Takes the problem set mentioned above (LP) and adds a calibration constraint:

$$x_i \leq \bar{x}_i \,(1+\varepsilon)\,[\rho_i]$$

  with $\bar{x}_i$ observed activity

  After running the optimization the shadow values of scarces resources (λ_j) as well as the calibration constraints ρ_i can be recovered.

- Step 2 : the PMP model Sets the PMP model and calibrates the model according to first order conditions of 1 stage and PMP. This yield the following condition:

$$\alpha_i + \beta_i x_i = \bar{c}_i + \rho_i$$

The alternative to this quadratic cost model is to consider the non-linearity in yields (and keeping costs linear as in the PL model).PMP models with increasing marginal costs and constant yields have been justified heuristically by decreasing marginal land quality. As such, they implicitly assume that yields would decrease with acreage were it not for the increased expenses incurred to keep yields constant.

This fixed proportion model can be written as:

$$q_i = \alpha_i x_i^{\delta_i}$$

with δ_i the return to scale parameter. The Constant Elasticity of Substitution model allows for substitution among j inputs and with $\sigma_i \in [0;1]$ the elasticity of substitution :

$$q_i = \alpha_i \left(\sum_{l=1}^{2} \beta_{il} x_{il}^{\frac{\sigma_i - 1}{\sigma_i}} \right)^{\left(\frac{\sigma_i}{\sigma_i - 1}\right)\delta_i}$$

The solutions for these two models are derived n Chapter 5 i.e. Graveline and Mérel (2013). The idea is to recover α_i and β_i as well as PMP cost adjustment terms from the first order conditions (FOC).

To solve the system resulting from the FOC (whatever cost or yield non-linearity is specified), three solutions are cited by Heckelei and Wolff (2003). These procedures are necessary because, the PMP model is underdetermined meaning restrictions have to be imposed to find a single solution to the optimization problem.

- simple ad-hoc procedures with some apriori parameter set, for instance setting $c_i = \alpha_i$ or setting off-diagonal elements to zero in the matrix notation (Howitt, 1995b),
- the use of supply elasticities (Helming et al., 2001; Mérel et al., 2011),
- the use of a maximum entropy criterion (Paris and Howitt, 1998).

The different specification of parameters involves different simulation behaviour, even if all solutions calibrate perfectly and replicate observed data. Heckelei and Britz (2005) explain that the estimation equation are biased, because parameters are estimated in a two-step phase. Furthermore, implied average cost will be higher than the observed one for preferable activities and marginal value for resources will be linked to marginal profit for marginal activities.

Other specification has thus been proposed in response to these remarks.

The use of maximum entropy specification

The maximum entropy principle developed in Golan et al. (1996) aims at solving underdetermined problems. They have been initially developed for econometric model estimation; an example is provided by Zhang and Fan (2001) who estimated production functions in China. Generalized maximum entropy (GME) consists in recovering parameters equal to a product between a set of probabilities and a set of support values (chosen by the analyst or consisting in prior information). The objective of the problem is to identify the probability distribution that maximizes the maximum entropy. The entropy of a distribution $\omega_i \in [0;1]$ is defined by $-\sum_i \omega_i \ln \omega_i$. The main work which introduces GME in the PMP approach is Paris and Howitt (1998) where the use of the maximum entropy is implemented to recover a fully specified matrix (step 2 of the PMP calibration). A lot of PMP experiments have used this technique, e.g. Arfini et al. (2008) who implement the GME framework to recover cost and demand matrixes for Italie from FADN (regional data) for PMP modeling. One of the main critiques addressed to the GME approach applied to quadratic cost functions calibration is that it relies heavily on the support values (ideally prior information but often arbitrary support values (Heckelei and Britz, 2000)) and that it lacks empirical foundations (Heckelei, 2002).

The Heckelei & Wolff *econometric* alternative

Heckelei and Wolff (2003) suggest a method to estimate (and not calibrate as in PMP models) production functions as an alternative to classical PMP which, they say, embodies inconsistencies in the shadow cost estimation. In fact their suggestion is to skip step 1 of the classical PMP (calibration constraints to recover dual values) and estimate simultaneously the shadow prices and parameters from the optimality conditions. They precise that second order conditions, i.e. curvature conditions, might need to be applied according parameter specification. This technique gets closer to the classical econometric approach. They suggest, using a quadratic cost function on a simplified model using the GME approach to estimate an error vector between optimal and observed land allocation and supply elasticity terms. The advantage of this approach is that no closed form solution is required, thus there is no prior constraint on the functional forms. See other specification rules in Heckelei and Britz (2005) (the CAPRI Model uses this form).

Other extended PMP forms

A first type of extension has been proposed by Heckelei and Britz (2000) who suggest making use of time series of cropping patterns in different regions and integrate cross cost effects to recover a full specified matrix.

Röhm and Dabbert (2003) suggest also an alternative to the classical PMP, it is well known under the *Röhm & Dabbert approach*. The rational for the extension is that there might be more substitution among same crops grown with different technologies than among different crops. This enable to calibrate production functions of alternative activities (e.g. organic / conventional crops) forcing some parameter to be the same. This technical choice can be discussed as same crops with different technologies will already have a number of parameters that will be equal or similar (price of product, costs etc.) allowing implicitly for more substitution. Blanco et al. (2008) showed with an empirical case study that this approach should not be applied to groups of crops (e.g. winter cereals), because it allows for too much substitution among different crops within the same group. However, this approach might be applied for different variants of crops as Röhm & Dabbert suggested.

Kanellopoulos et al. (2010) suggest and analyze a PMP variant that raise the problem that the gross margins of the least profitable crop is zero (in the calibration phase) by introducing the land rent cost in the objective function and distinguishing activities that are above the average gross margin (type A) and those that are lower than the average gross margin (type

B). The first step includes two types of calibration constraints: (i) the classical $x_i \leq \bar{x}_i(1+\varepsilon)$ calibration constraint for type A activities and (ii) $x_i \geq \bar{x}_i(1+\varepsilon)$ calibration constraints for type B activities.

Calibration on supply responses with supply elasticities

As illustrated by Heckelei and Britz (2005); Mérel and Bucaram (2010) some developments of PMP are concerned with a more realistic response to price signals and suggest calibrating the model against exogenous supply price elasticities. These elasticities should then be provided from econometric estimates or, when not existing, through expert knowledge. This refinement enables to avoid the caveat of unrealistic supply response patterns that could appear for arbitrary calibrated PMP models. Calibration on supply elasticities is possible for either non-linear cost (see e.g. Heckelei and Britz (2005); Mérel and Bucaram (2010) or non-linear revenues with fixed proportion or Constant Elasticity of Substitution of inputs Mérel et al. (2011) functional forms. Technically calibration on this extra information is possible because the problem is underdetermined as detailed above. Concerning the non-linear revenue forms, two alternative techniques are distinguished by Mérel et al. (2011). The first consist of a myopic calibration that doesn't account for changes in shadow values of linear constraints. The second called "generalized CES model" allows for shadow price adjustments.

For any of both techniques, these types of model require robust data on own supply elasticities which is, for the majority of locations, difficult to obtain. For instance, the CAPRI model in Europe has recently produced a large data set at (administrative) regional scale (Jansson and Heckelei, 2011) but the results are not pure econometric estimates (they are recovered with a Bayesian estimation method). Overall few recent supply elasticity data exists. As explained by Mérel et al. (2011) existing supply elasticities often imply constraints on resources (notably land). As such the calibration on supply elasticities must allow for shadow price adjustments with output price changes, when the constraints are included in the model. Mérel and Bucaram (2010) derive the sufficient and necessary conditions under which quadratic cost models can be calibrated against exogenous supply elasticities. Mérel et al. (2011) analyze the non-linear revenue/yield counterpart with linear cost terms and argue for this functional form. Two alternative of this model are developed (i) the fixed proportion case and the (ii) CES model allowing for substitution among inputs. This last option is, at first sight, particularly interesting when dealing with environmental policy experiments (quantitative or qualitative water management issues).

Appendix 3 : Models that integrate risk

The main models that enable to deal with risk in agricultural modeling are presented in the two next paragraphs. Other specifications are the safety first model, the Mean-Gini, the additive utility or direct expected maximizing non-linear programming exist (see Hazell and Norton (1986); Bouzit (1996) for a review). Some can be combined with each other: for instance when one method deals with integrating risk the objective function and the other in the constraints (see for instance Paris and Easter (1985) who combined mean-variance and chance programming).

The mean-variance analysis

The expected income-variance (E-V) model assumes that farmers hold preferences according to the expected income and income variance (E-V utility function) by minimizing variance and parameterizing income from 0 to unbounded (Hazell, 1971). This model defines an efficient E-V boundary for varying levels of income that enable to select optimal farm plans according the farmers E-V utility function. The Markowitz (1959) problem (portfolio selection) minimizes the variance for alternative levels of expected returns. Freund (1956) was the first to apply this type of model to agricultural farm planning. His model, which is known as the E-V model can be written as:

$$\max EV = \sum_i \bar{c}_i x_i - \Phi \sum_i \sum_k \sigma_{ik} x_i x_k$$

with i activities, k time index of series, x_i activity levels, $\bar{c}_i$ the mean net returns or gross margins and σ_{ik} its covariance, Φ the risk aversion coefficient

The generalized MOTAD model

The expected income-mean absolute income deviation model has been introduced by Hazell (1971) as a linear approximation to the E-V model. It is known under the MOTAD ; it stands for "minimization of total absolute deviation". It must be considered as a linear approximation of the E-V model. Here the measure of risk is the absolut deviation formalized as follows:

$$\begin{aligned} &MAD_i = F\left[\tfrac{1}{T}\textstyle\sum_t(\phi_{i,t}-\bar{\phi}_i)^2\right] \\ &\text{with } \; F = \tfrac{2}{T}\sqrt{\tfrac{(T-k+1)(T+1)\pi}{2T(T-1-k)}} \end{aligned} \tag{2.3}$$

and the model is as follows:

$$\max_{x_i \geq 0} \Pi = \sum_i \left(c_i x_i + \Phi\sqrt{MAD_i}\right) \tag{2.4}$$

$$\text{subject to} \sum_i x_i \leq b_{land}\,[\lambda_j]\,. \tag{2.5}$$

with MAD_i the mean absolute deviation,
F the Fischer coefficient,
Φ the risk aversion coefficient (the calibration parameter),
T the number of years in the time series,
k the number of activities,
$\phi_{i,t}$ the product of prices times yield for year t and crop i and $\bar{\phi}_i$ the mean of $\phi_{i,t}$ over t years,

This model was then generalized: both maximization of profit and minimization of absolute deviation were integrated in the objective function, and called the “generalized MOTAD” by Hazell and Norton (1986). The idea is to express the variance as the mean absolute deviation from the average income. The major advantage above the E-V criteria is that this enables the specification of a linear model, which was easily tractable computationally, historically. A detailed treatment of the question is provided by McCarl and Spreen (1997). They are different ways to integrate the absolute deviation in the classical production model. Two alternatives are presented in Chapter 3 and 4. The first is the integration of a risk term in the objective function, it enables to consider production (prices*quantities) variation in the past and the second is the integration of a risk term in constraints of the model. It enables to integrate a variation on the resource or on the level of resource use (Leontief coefficient).

An alternative to the general MOTAD presented here is the Target MOTAD which accounts for the deviation from a target level of returns (see Tauer (1983)).

Chapter 3

Combining economic and groundwater models for developing long term nitrate concentration scenarios in a large aquifer

Note the work presented in this essay started in 2004, this is why the future horizon (2015) appears too close now, but it was, in 2004, a real mid-term future horizon.

3.1 Introduction

During the late 1980's, the concerns expressed by the public in Europe about steadily increasing nitrate concentrations in drinking water resources triggered a policy debate on agricultural non-point source pollution. This led to the Nitrate Directive (91/676/EEC) in 1991, followed by a first wave of actions in the farming sector supported by Member States. A publication of the European Commission (European Commission, 2002) reviews the measures implemented between 1991 and 2000 and showed that these measures have not been sufficient to reverse the trend and to achieve the targeted nitrate concentration of 50 mg/L in all declared vulnerable areas. This statement particularly applies to groundwater bodies, a number of which still showed increasing nitrate concentration trends and are increasingly concerned by diffuse pesticide pollution. This debate has been revived with the publication of the Water Framework Directive (2000/60/EC) which requires Member States to maintain or restore - "good chemical status" for all water bodies by 2015 (see Introduction Chapter).

A key issue that policy makers and water planners need to investigate is the expected future evolution of groundwater quality. This requires understanding and modeling the dynamics of groundwater quality. The approach presented in this chapter recognises that water quality evolution is not only determined by bio-physical drivers (such as climate, groundwater flows, etc.) but also by economic drivers which considerably influence the activities generating the pollution; and that cropping activities might have a significant different impact according crop.

As discussed in Chapter 1 (1.3.2) nitrate contamination is a major issue in the Upper Rhine Valley aquifer because several areas overpass the regulatory threshold of 50 mg/L and the WFD risk assessment has classified the groundwater body at risk of not achieving the good chemical status in 2015 because of nitrate contamination among others (pesticides are also a reason of disclassification).

This chapter presents the result of an economic research study that assesses the future cropping patterns and practices in the upper Rhine aquifer influence area (German-French boarder). To achieve this the two main tasks were (i) identifying the driving forces likely to influence future agriculture practices (e.g. crop choices, use of fertilizers) and combine them in scenarios and, (ii) assessing the impact of previously defined scenarios in terms of cropping patterns and practices using mathematical farm programming models. The results were then entered into a bio-physical modeling chain designed to estimate the impact of those changes on nitrate contamination and groundwater quality. This work was conducted as part of the trans-boundary MONIT InterReg project which aimed at assessing the evolution of nitrate contamination based on the development of an integrated modeling platform of the upper Rhine valley aquifer. The bio-physical part of the modeling platform, which has been detailed in Grimm-Strele et al. (2005); LUBW (2006) comprises a soil-plant model (STICS, simulation of nitrate transfer in the unsaturated zone), a nitrogen balance model (simulating nitrogen infiltration in the aquifer, STOFFBILANZ), an hydrogeological model that simulates water and nitrogen flows in the aquifer and an economic model (simulating farmers' decisions in terms of crop choices). The present chapter focuses on the development of the economic model and the scenarios construction at the very beginning of the modeling chain. We detail how the methodological choices have been driven by the finality of water resources assessment. Selected examples of simulation runs are presented in the last section of this Chapter: (i) the CAP scenario, (ii) the global scenarios, (iii) the tax simulation on both fertilizer use and on the post harvest nitrate residual content for two farm types.

3.2 Overview of the hydro-economic modeling chain

The integrated modeling platform comprises three main compartments[1]. The overall architecture and parameter exchanges are presented on Figure 3.1. The first model in the modeling chain is the economic farm optimization model on which we concentrate in this chapter. The choice of this methodology has been detailed in the Review Chapter. It aims at representing crop choices and fertilizer use practices for all the farms in the area of interest. The economic model results are cropping patterns and practices per modeled farm type. To provide this data to the remaining modeling chain these results were extrapolated on the whole area. As such the economic model results could be expressed in total usable farm area over the aquifer. These results were than transformed into a vector of percentage area evolution per crop, per small agricultural regions ("Petites Régions Agricoles", PRAs) and per scenario and used as input to the nitrogen balance model (STOFFBILANZ, Gebel et al. (2003)).

[1] They are further detailed in (LUBW, 2006)

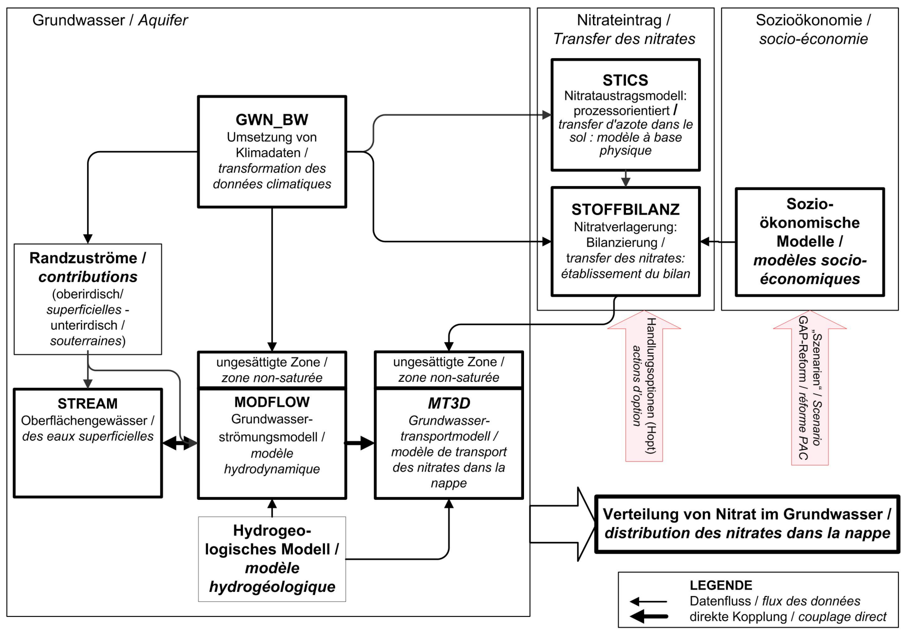


Figure 3.1: Overview of the model chain and interactions. Source : Lubw, 2006

STOFFBILANZ calculates nitrogen balance in the non-saturated zone on a 500 m * 500 m cell size and on a yearly time scale. The calculation is a balance and includes a simplified calculation of the nitrogen cycle in the soil. It accounts for (i) sources of nitrogen among which mineral and organic (animal) fertilizer application, atmospheric deposits, symbiotic fixation, mineralisation, nitrogen mobilisation from harvest residues; and (ii) for sinks of nitrogen among which harvest exportation, residues and denitrification[2] according soil and texture.

The parameters of this nitrogen balance model are adjusted using a soil-plant model STICS (*Simulateur mulTIdiscplinaire pour les Cultures Standard*; Brisson et al. (2003)) which is developed and calibrated for different crops and types of soils. It simulates the carbon, water and nitrogen balances of the system. STICS is also used to analyze in detail the impact of agricultural management options.[3] It represents the soil-plant-atmosphere system and in particular (i) the soil and plant water content, (ii) the soil and plant nitrogen content and (iii) crop growth. The parametres of the model include pedological characteristics: water

[2]chemical transformation of nitrate into gaz favoured by bacterias

[3]Some of the models of MoNit were also used to assess the impact of alternative management options such as reduction in fertilizing practices or adopting particular practices. See Lubw, 2006. We do not detail this part in this chapter

capacity, gravel, humus, clay and calc contents. Five different climatic zones have been considered for the precipitations characterization.

The results of the nitrate balance model STOFFBILANZ are then fed into a three-dimensional groundwater flow model which simulates groundwater flows and levels as well as nitrogen transport within the aquifer. The hydrogeological model employed is MODFLOW (Harbough et al., 2000) and is combined with the MT3D package which simulates the transport and the denitrification, and the STREAM package which simulates surface hydrology including the surface-groundwater exchanges. The spatial resolution of MODFLOW is 100 m * 100 m and, vertically, 10 layers within the aquifer have been considered. The recharge of the aquifer has been modeled with GWN-BW (Menzel, 1997) a soil-plant-atmosphere system representation that requires meteorological data and soil occupation. This module has a resolution of 500 m * 500 m.

3.3 Farm models to assess the evolution of agricultural land use and nitrogen practices

3.3.1 Overview

The economic model consist in representing the behaviour of farmers with respect to input allocation on crops and concretely their choice of cropping patterns and agricultural practices in the upper Rhine aquifer influence area. The economic methodology developed and implemented consists of eight steps interlinked as shown in Figure 5.2 below. They can be gathered in two main parts, the first is dedicated to the model set-up, the second focused on scenario definition and simulation. During all the process, a group of experts was regularly consulted for validation of the assumptions and results.

The first step consists in defining a limited number of small agri-environmental regions homogeneous in terms of geographical and environmental characteristics (slope, type of soils, climate) and land use (share of forest, arable land, grassland, etc). The second step consists in constructing a farm typology to characterize farm types in both Alsace and Baden. Twelwe main farm types were selected based on their nitrate contamination potential (we detail this in 3.3.3) for modeling. Real farms that are representative of the typology are then selected in collaboration with local extension offices and interviews were carried out in order to describe farmers' production strategy, assets and constraints (step 3).

Micro-economic models are developed for the selected farm types (step 4). These models assume that farmers select the combination of crops which maximises their income under a set of technical, regulatory and economic constraints. They simulate crop choices, input consumption (fertilizer, labour, energy) and farm income for different input parameter values (agricultural prices and subsidies, regulatory constraints, changes in the price of input such as energy, fertilizer, labour, minimum set aside constraint, etc).

The second group of tasks was dedicated to scenarios construction and simulation. First, a group of expert is consulted (step 5) to identify major driving forces (or factors of change) likely to influence farm decisions in the medium term. These factors of change are sorted according to the impact they might have on diffuse pollution, their uncertainty, the time horizon when the change is likely to occur and the ability of the farm models to simulate their impact. Expected evolution trends are then described for a limited number of driving forces, based on experts advise and litterature. They are combined in three coherent scenarios corresponding to different evolutions in the overall (exogenous) context. Policy makers, who are full members of the project, are consulted to identify possible policy responses to the anticipated evolution (step 6); a list of regulatory, contractual and economic measures is developed, taking into account the existing regulatory framework at EU, national and regional levels, existing local policy instruments and a review of measures implemented in EU Member States to reduce nitrate pollution levels.

Step seven consists in running the models to assess the changes associated to each of the combined scenarios.

Finally, the results of the farm models are extrapolated to the small agricultural regions and used as input by the nitrogen balance model (step 8).

3.3.2 Farm typology

A farm typology is the description, characterization and quantification of typical farm types in a given region. It aims at describing the agricultural sector and its diversity from a spatial and structural point of view. It is a classical approach in agricultural economics which enable to have a simplified but quantitative representation of agriculture. This a necessary approach when modeling individual farms that should be representative of large groups of farms. The fact that there are representative is convenient when there is a need, such as in our case, to extrapolate results to the entire area. The objective is to group in a same type, farms that have a similar structure in their production, the same major activities (crops

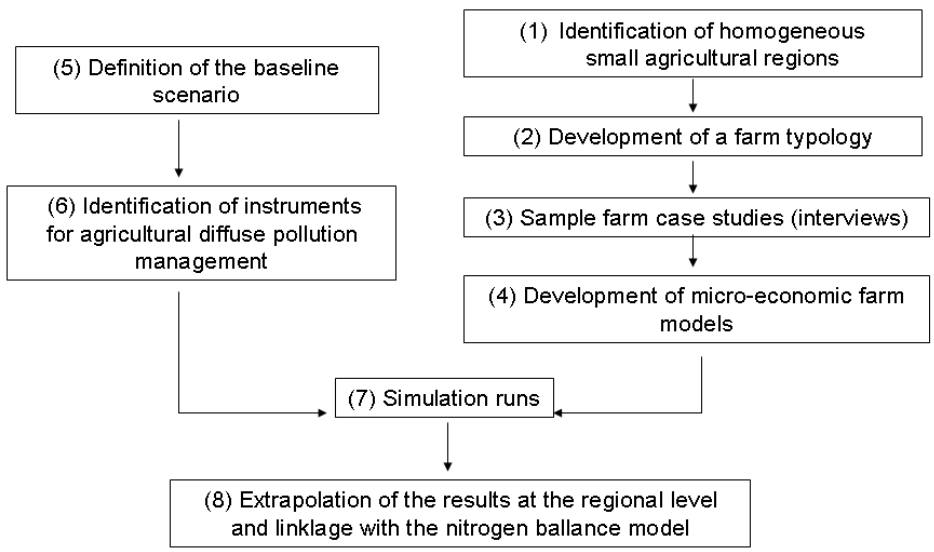


Figure 3.2: Major steps of the methodology

or livestock), similar strategies and constraints (Palacio et al., 1995). A good typology has to show maximum heterogeneity between farm types and maximum homogeneity among farms within a given type (Köbrich et al., 2003).

The set-up of a typology consists in the classification of a population of farms in types, this can be conveniently done with automatic classification methods (Ascending Hierarchical Classification, k-means cluster analysis), but requires individual data. When types are satisfying in terms of number and of diversity and homogeneity, a typical farm type is characterize to be representative of each type. We will model these typical farms.

3.3.3 Potential of nitrate leaching per farm types

In order to reduce the overall number of farm types to be modeled, we select farm types that contribute most to the nitrate contamination. To this aim we set-up and calculate a simple indicator of the relative potential of nitrate leaching generated by the different farm types. The use of detailed nitrogen balance models[4] was not possible in our case, given the aggregate level at which the analysis is carried out and the lack of information on farm practices (quantities of fertilizer used, manure spreading practices, etc) at this stage of the project. We therefore used a simpler indicator to assess the relative contribution of each farm type to the potential of nitrate leaching. This indicator was defined as follows:

$$R_z = \sum_i S_{zi} k_i$$

where: z is the farm type index, i a crop index, R_z the farm type specific nitrogen leaching potential, S_{zi} is the area of crop i cultivated by farm type z, k_i is the post harvest residual nitrogen for crop i per hectare (two different soil types were considered: Hardt and other, lime dominant soils).

This is a simplified approach as no difference was made in respect to variable soil types and practices that differ obviously among locations and farms. However, this approach enables to select farms based on a simplified indicator instead of deciding arbitrarily which farm types to model.

[4] such as the STOFFBILANZ model or CORPEN model in France

3.3.4 The economic model

Economic programming models for environmental impact assessment

Programming models have often been used to model agricultural policy implications (Boussard et al., 1997; Barkaoui and Butault, 2000; Arfini et al., 2005) and, more recently, the evolution of land-use and practices in farming in order to simulate the environmental impacts of these changes (Lambin et al., 2000; Busch, 2006). Several authors use linear programming (LP), which can model decision-making on the scale of an individual farm by explicitly representing the technical and economic constraints faced by farmers (mainly land and water resources constraints, fertilizer or feeding constraints, crop rotation and environmental constraints), (see Bazzani et al. (2004); Bartolini et al. (2007); Acs et al. (2010). Models using the Positive Mathematic Programming method (Howitt, 1995a) can be developed when constraints are not known in detail or technical data is not available at farm scale as discussed in Chapter 2.

We considered that linear programming was more relevant than Positive Mathematic Programming (PMP) in the present case, although this method has been widely used in recent years. The two main disadvantages of LP are that it produces discontinuous responses (thus extreme or not reactive to changes), and often produces over-specialized situations (Gohin and Chantreuil, 1999). On the other hand, the capacity of LP models to account for constraints at individual farm scale is a major advantage for simulating interactions between economic dynamics and biophysical processes, which is one of the issues at stake, particularly regarding constraints on water and nitrogen management and demand. Linear programming is therefore considered more appropriate than PMP on this scale, where enough technical constraints can be made explicit to avoid overspecialisation (Heckelei and Britz, 2005).

Among the studies aiming to assess the environmental impacts of economic trend scenarios in agriculture, one can refer to Topp and Mitchell (2003), which simulate the impact of the Common Agricultural Policy reform on landscapes, by coupling LP models with a specialised land-use model. Concerning water contamination issues, Schwabe (2000); Haruvy et al. (1997) use LP models to assess and compare the costs that would arise from reducing nitrates if statutory inspections or incentives were introduced. With the same idea in mind, Meyer-Aurisch and Trüggelmann (2002) have modelled the behaviour of a farm opting for different cultivation practices and tested the economic impacts of sub-optimal fertilizer inputs. In Denmark, Berntsen et al. (2003) have used LP to optimise the behaviour of farmers who have to pay taxes on fertilizer use or on pollution arising from their use. Finally, some of these models have been integrated or coupled with other sub-models capable of representing physical, agronomic or pollutant transfer or transport processes in soils or water (Haruvy et al., 1997; Vatn et al., 1999). They can also be coupled with a geographic information system for spatial impact analyses (Giupponi and Rosato, 1995).

The model

The farm supply models aim at simulating farmers' behaviour in terms of crop choice and cropping practice (e.g. fertilizer use, intercrop soil management practices, etc.) for different economic conditions. A different model is constructed for each type of farm. Models assume that farmers select the combination of crops which maximises their income under a set of technical, regulatory and economic constraints (Hazell and Norton, 1986). They enable to simulate crop choices, input consumption (fertilizer, labour, energy) and farm income for different input parameter values.

We first specified our model as follows:

$$\max_{x_i \geq 0} \Pi = \sum_i \left(p_i q_i - x_i \sum_j c_j a_{ji} \right) \quad \text{with } q_i = y_i x_i$$
$$\text{subject to } \sum_i x_i \leq b_{land} \; [\lambda_j]$$

with Π profit, x_i area allocated to crop i or heads of animal production i, y_i the yield per unit of activity i, q_i the quantity produced of commodity i, a_{ji} the amount of input j used (here land, energy, fertilizer and water) also called the Leontief coefficient as all inputs are used in fixed proportion with land, c_j the variable cost per input j. b_{land} is the resource availability in land and λ_j the shadow value of input j (land here). Here it is the unique limited input. Specific quotas are also limited but not specified in this the general formulation. The gross margin of crop i are referred to as $GM_i = p_i q_i - x_i \sum_j c_j a_{ji}$.

The model further integrates technical and regulatory constraints that have been formalized after detailed face to face interviews of representative farm managers for each farm type (detailed in the calibration paragraph).

This LP model systematically allocates land to the crop with the higher gross margin unless a specified constraint avoid the model to do so. This is why correct gross margin and constraint characterization are very important. Even when taking care in the characterization of both gross margins and constraints, models can still be far from replicating the observed land allocation. One possible interpretation is that the farmers' objective function is not the one specified and that he values the risk on revenues i.e. the variation in gross margins (yields and prices) that he observed in the past and anticipate similar variation in the future. For instance, if one crop observed higher gross margin variation then another with similar medium gross margin he will prefer the one with less variation (standard deviation). Indeed when he maximises his revenues the farmer can only assume the values of both prices and yields that will form his future revenue based on his knowledge of these values in the past and his expectations for the given year. Another interpretation for the absence of replication that is common in the literature is that all costs are not observed. This approach is known under the Positive Mathematical Programming approach and is detailed in the Review chapter and implemented in Chapter 5.

To account for the variation in prices and yields and consequent risk on revenues from the farmers' perspective and to improve the replication of the observed situation we adopted the LP MOTAD (minimization of total absolute deviation) model formulation (Hazell and Norton, 1986). It adds a variance-like term to the standard LP problem that accounts for variation in revenues (prices and yields). It has the computational advantage of being also a linear model while accounting for risk [5]. Other programming models that integrate risk are rarely linear (see Chapter 2). The formulation is as follows (farm index z is absent for notational simplicity; we simplify the model by writting $c_i x_i = \sum_j c_j a_{ji}$, because all inputs are in fixed proportion with land[6]):

$$\max_{x_i \geq 0} \Pi = \sum_i x_i \left(p_i y_i + \Phi \sqrt{MAD_i} + CP_i - c_i \right) \tag{3.1}$$

$$\text{subject to} \sum_i x_i \leq b_{land} \left[\lambda_j \right]. \tag{3.2}$$

[5] It is, however, becoming less an argument with the development of softwares like GAMS that enable non-linear problem solving

[6] See Review Chapter for more details

$$\text{with} \quad \begin{cases} MAD_i = F\left[\frac{1}{T}\sum_t(\phi_{i,t} - \bar{\phi}_i)^2\right] \\ \\ F = \frac{2}{T}\sqrt{\frac{(T-k+1)(T+1)\pi}{2T(T-1-k)}} \end{cases} \tag{3.3}$$

with the same notation as in the previous model and with MAD_i the mean absolute deviation, which represents the variation of revenues, i.e. of prices times yields (product per hectare) of the main crops over nine years. The least intensive crops (especially those receiving little irrigation or fertilizer) are characterized by a major variability.
F the Fischer coefficient,
Φ the risk aversion coefficient (the calibration parameter),
T the number of years in the time series,
k the number of activities,
$\phi_{i,t}$ the revenue (product of prices times yield) for year t and crop i and $\bar{\phi}_i$ the mean of $\phi_{i,t}$ over t years,
CP_i the CAP premium coupled with activity i (in some cases the irrigated and rain fed practice do not receive the same premium, which means that there is an implicit irrigation premium in the reference situation).

3.3.5 Data

Zoning

The economic models are farm models. However, the scale chosen for the economic and bio-physical model connexion (or data exchange) is the *Small Agricultural Region* (or PRA Petite Région Agricole). PRAs have been defined in France in 1956, they correspond to homogenous agricultural areas from both the soil and climate characteristics as well as broad characteristics of farms. For computational reasons a smaller scale connexion was not possible and this scale appears to be a good trade-off between model precision and computational feasibility. Figure 3.3 shows the PRA on the Alsatian border and the equivalent zoning in Baden. The german zoning has been realized for the project by the expert group in the same logic as the french PRAs.

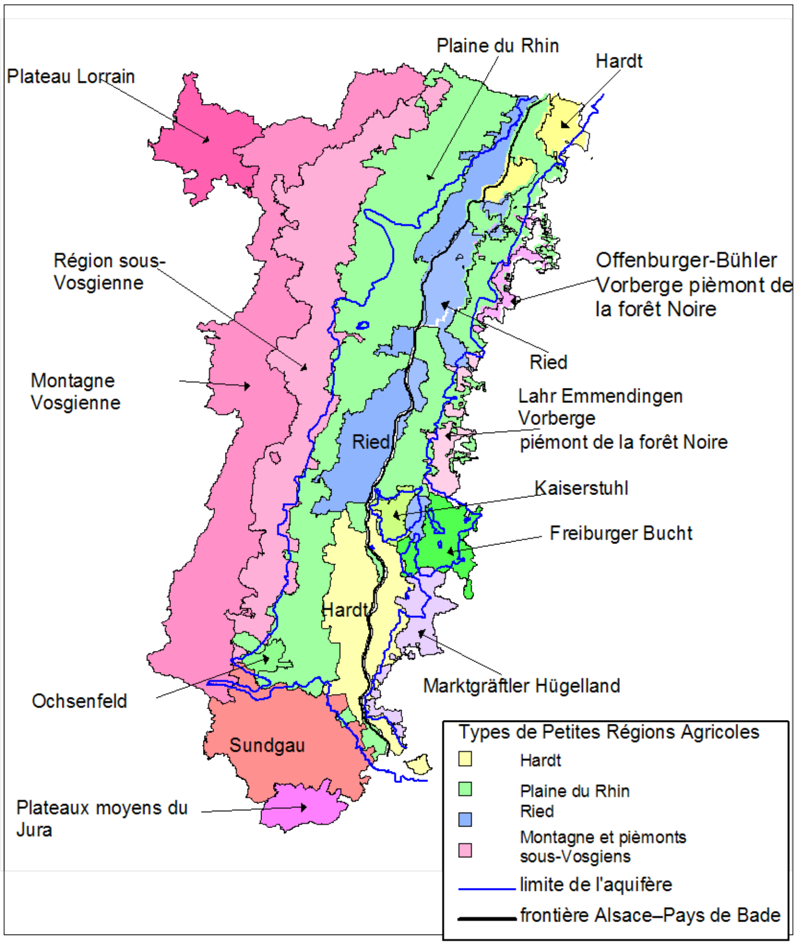


Figure 3.3: PRAs and aquifer delimitation: only PRAs included in the aquifer zones have been considered. They are further divided into Haut-Rhin and Bas-Rhin in France

Agriculture in the upper Rhine valley and farm types

The typology was based on a farming system analysis conducted by the regional Agriculture Chamber (Chambre d'Agriculture Régionale d'Alsace, 2003) and farm statistical classification conducted by LEL in Germany as part of the project. Is is detailed in Graveline et al. (2004a).

In Alsace and Baden-Württemberg respectively, 16 and 11 farm types were identified, with some correspondence between most of the types and some specific types are only present in Germany or France. Approximately 80% (France) and 66% (Germany) of the farms, representing between 85 and 81% of the total farming area, could be classified into one of the types. The remaining farms which did not correspond to any of the types defined by experts are left out of the sample for the study. The major types identified are described in Appendix 3.8 together with their frequency in the area.

C1, C2, C3, C4 and C5 are cereal-corn oriented farms that differ in terms of size, level of diversification and intensification. L farm types are milk producers. D farm types are diversified with special crops and cereals and oilseed crops. V2 are vine producing types, with a small share of cereals and corn.

Estimation of potential nitrate leaching and selection of modeled types

The post harvest nitrogen residual values used are estimated using the results of the 2001 - 2003 campaigns of the SchALVO program implemented in the land of Baden Württemberg. This program consists in analysing nitrogen residual in soil (90 cm depth) after harvest in all the fields located within drinking water protected areas ("Wasserschutzgebiet"). Since farmers are charged with a fine if the residual exceeds a certain threshold value, it is expected that the nitrogen residual content of the soil is lower in these protected areas than in other regions. Nevertheless these values can be used in order to assess comparative and relative impact between crops.

The indicator of potential nitrate leaking R_z is calculated for each farm type and soil. The Figure 3.4 gives the relative impact of each farm type. This enables to select only the farm types that contribute most to the nitrate contamination.

The results show that 7 farm types contribute to respectively about 78 and 85% of the total post harvest nitrogen residual in the soils in Baden and Alsace. The total contribution of the five cereal oriented types is very significant (59% in Baden and 56 % in Alsace).

Diversified vine oriented farms in Alsace (V2) and vine-orchard farms in Baden are also significant contributors (11% in Baden and 10% in Alsace) as well as diversified farms (9% in Baden, 12% in Alsace). These farm types therefore represent a priority target and specific measures should be implemented to reduce their nitrogen emission.

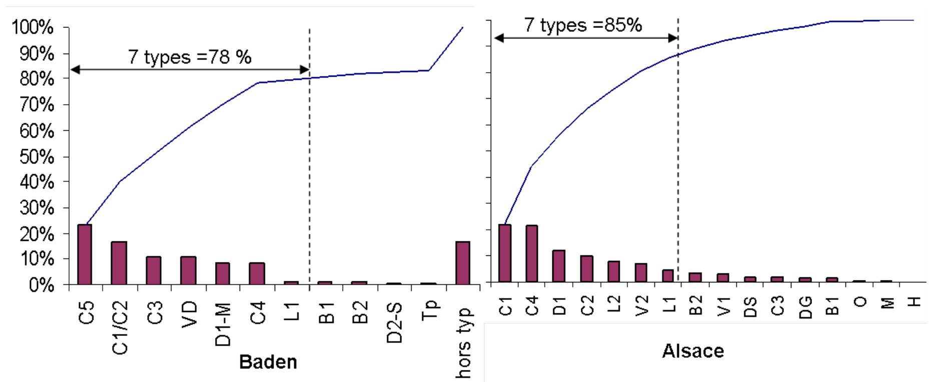


Figure 3.4: Contribution to the total potential of nitrate leaching per farm type and selection of farm types that contribute most. Tp designates all other small farm types

We then merge similar types L1 and L2 in Alsace into the L type. In Baden, we further choose not to model very specialized farms (VD and D1-M). As a result 6 types were modeled in each country.

Table 3.1 gives some details about the French model types.

Economic and technical data

The number of each farm type in each PRA was recovered from the typologies to enable extrapolation.

30 activities were considered in the model to represent the variety of activities among farm types. The activities as well as their main characteristics are given in Table 3.2. Milk and sugarbeet productions are limited by individual quotas. Tobacco and rape are contract crops and are also considered as limited.

A production function, linking corn crop yields and nitrogen input was developed using agronomic field test conducted on different soils in the region.[7] This allows defining three

[7]This work was realized during the MoNit project by ARAA (Association pour la Relance Agricole en Alsace.

Farm type	C1	C2	C4	D1	L	V2	Total
	Corn grower (with irrigation)	Corn grower	Small part-time farm	Diversified farm with a majority of corn	Dairy farm	Wine grower	-
Nb of farms	353	248	2 925	464	651	3 196	7 837
UFA* (ha)	85	80	15	56	70	10	-
Total (ha)	30 005	19 840	43 875	25 984	45 570	31 960	197234
Main crops	Corn (part irrigated), wheat	Corn, wheat, sugar beet, grassland	Corn, grassland	Corn, Wheat, Sugar beet Rape, Tobacco, Grassland,	Fodder corn, corn, wheat, barley, sugar beet, grassland	Wine, Corn	-

Table 3.1: Characteristics of the French farm types.*: Usable farm area

different levels of fertilization intensity that the model will integrate and select according to conditions. Due to data availability constraints, the production function could only be developed for corn, which represents the main source of nitrate input in the aquifer. We indicate the levels of nitrogen fertilizer use, note that other fertilizers (potash and phosphate) are used in fixed proportion with nitrogen for a given crop. The values are also reported in a Graph (see Appendix 3.8).

Gross margin values are calculated from different sources. Our calculation includes all variables costs including the variable machinery cost (that are not accounted for in French standard gross margins, but in German standards). We calculate as specified in the model, cost related to each of the inputs: energy, water, fertilizer and affect all other inputs to land. As such the total variable cost integrates the seeds, water, fertilizer, pesticides, insurance, energy (machines and drying of corn) and external labour when required for growing the crop. For animal production the variable cost integrates mainly the feeding of the animal (when not grown on the farm), the provision of young animals, insurance, energy (machines) and other costs (mainly health related).

In Baden data from Landesanstalt für Entwicklung der Landwirtschaft und der ländlichen Räume-Schwäbische Gmünd" (2003) and KTBL (Kuratorium für Technik und Bauwesen in

Activities	type	risk*	Yield (in qx)	Input use/ha/year N (Kg)	Water (mm)	Diesel (L)	Price w/o premium (€/qx)	Gross margins (€/ha)
wheat	X	yes	70	120	-	112	10.9	731
wheat - Hardt	X	yes	72	165	-	112	10.9	727
winter barley	X	yes	65	80	-	112	10.3	651
corn silage (production only)	X	-	120	180	-	95	0.0	-916
corn irr. 1 (low fert.) -Hardt	x	yes	106	190	120	506	13.1	830
corn irr. 2 (mean fert) -Hardt	x	yes	111	210	120	518	13.1	867
corn irr. 3 (high fert.) -Hardt	x	yes	114	230	120	526	13.1	882
rainfed corn (high fert.) -Hardt	X	yes	65	165	-	243	13.1	497
rainfed corn 1 (low fert.)	X	yes	101	150	-	331	13.1	910
rainfed corn 2 (mean fert.)	X	yes	104	170	-	339	13.1	925
rainfed corn 3 (high fert.)	X	yes	106	190	-	344	13.1	929
rape	Q	yes	30	120	-	75	24.0	569
industrial rape	X	-	30	106	-	150	21.0	414
rape for raw oil	x	-	20	106	-	-925	12(cake)	257
sugarbeet	Q	-	750	45	-	107	3.3	2806
sunflower	X	-	29	70	-	75	21.0	347
soy bean	X	-	30	0	-	75	22.0	336
tobacco	Q	-	29	120	200	448	116.0	7454
vegetables	x	-	35	130	200	1668	500	12086
wine	x	-	80	50	-	850	110	5727
permanent grassland	X	-	80	120	-	90	-	-590
temporary grassland	X	-	90	150	-	120	-	-637
hay	X	-	1	-	-	0	11	11
grass fallow (premium)	X	-	-	-	-	20	-	317
grass fallow (no premium)	X	-	-	-	-	20	-	-110
permanent fallow (premium)	X	-	-	-	-	3	-	427
permanent fallow (no premium)	X	-	-	-	-	3	-	0
IWCC	X	-	-	-	-	0	0.0	58
Animal production								
milk cow	Q	-	7500	-	-	-	0.25	2174
heifer	x	-	1	-	-	-	855.0	270

Table 3.2: Model parameter values. X : activity that can be grown by all types; x can only be grown by certain types of farms; Q : activity submitted to contracts or quotas; *: Taking account of risk on yield*prices; fert. : fertilization; IWCC: Intermediate winter covering crop.

der Landwirtschaft) have been used. In Alsace, data from the Management centre of the Agricultural chamber of Bas-Rhin from 1997-2002 and from the Governmental Agricultural Statistics Office (SCEES) have enabled the calculation of gross margins. A price index from INSEE enabled to have prices in 2003 value.

Technical coefficients (input requirements) are based on figures reported by farmers during farm interviews. They were cross checked with standard values used by agricultural experts and published by professional agricultural organisations.

The series of prices and yields that are used to calculate the mean absolute deviation over a 9 year period are given in Appendix.

3.4 Calibration of the economic model

Technical and regulatory constraints

As discussed in the review chapter the calibration of linear programming models can not be a perfect calibration, mainly because the model has not sufficient degrees of freedom and not enough flexibility. However, we can consider the stage where the effects of constraints are tested on model behaviour, a first calibration stage.

First, all constraints are characterized based on farm interviews. These constraints concern cropping rotations, production quotas (dairy) or, animal feed rations and contracts for industrial crop production.

The constraints present in the Alsace models are the following.

Technical constraints on land:

- The irrigated area (irrigated corn, tobacco, vegetables) must be less or equal than the available land that is equipped with irrigation.

- Maximum 30% of the total farm area is dedicated to biofuel crops on each farm.

Regulatory constraints:

- Fallow land constraints depend on each scenario (evolution with CAP reform). In the reference situation fallow land must be at least 10% of the total land, and maximum 30% of the sum of areas dedicated to cereals, oilseeds and pulses.

- The activation of the area based direct payments (DP) imposes both that fallow land (for specific fallow direct payments) and crops (for normal direct payments) are effectively grown on the same amount of land.

- The Nitrate Directive imposes a maximum organic fertilizer load of 170 kgN/ha. One cow produces 80 kg nitrogen per year.

Technical constraints concerning crop rotations:

- Sugar beet and tobacco have to be preceded by wheat (equation is : $x_{Sugarbeet} + x_{Tobacco} < x_{Wheat}$),

- Oilseeds (Raps and Sunflower) can represent maximum 25% of the arable land (fallow land excluded) because they should not be grown more than every four years on a given land.

- Winter cover crop can be grown after cereals, forage corn and soy.

- Wheat and barley have to be alternated with other crops ($x_{Wheat} + x_{Barley} < 1,5 * x_{othermaincrops}$).

Animal feeding constraints:

- For each cow a minimum requirement of on-farm forage corn is required.

- A balance of hay is also calculated between the own production and the amount of hay that need to be bought out of the farm.

Calibration on the risk aversion parameter

The second and more classical calibration stage is to calibrate the risk aversion parameter Φ_z so as to replicate best the observed cropping patterns. Calibrated risk aversion parameter are given in Table 3.3. The higher the risk aversion parameter is, the higher the farmer is risk averse and values negatively the variation of its revenue. If the risk aversion is zero, than the farmer is risk neutral and the model becomes the general formulation without the mean absolut deviation term. The calibrated values make sense here. The irrigation strategy of the large C1 type can be interpretated as a way to reduce a certain part of the risk (yields) and results in a non valuation of risk in the objective functon. Types D1 and V2 which have both large revenues per hectare and per farm because they grow high value crops can also be understood as risk neutral, as risk aversion is often assumed to be decreasing with revenue. Conversely, small types that grow less intensive crops (in the sense of the revenue per hectare) are more risk averse. This is coherent with the classical assumption of (with revenu) decreasing absolute risk aversion[8].

Alsace types	C1	C2	C4	D1	L	V2
Φ	0	0.9	0.5	0	0.5	0
Baden types	C1	C2	C3	C4	C5	L
Φ	0	0.3	1	1.5	0	0.5

Table 3.3: Risk aversion parameter for the modelled farm types

The models are developed using a mathematical solver and a simulation engine developed using Visual Basic which allows repeated simulations for a range of input parameter values.

The validation of the model is not possible because we can not compare the model behaviour with observed data that do not exist (future). The validation is realized during a long procedure that involves discussions with experts about the realism of model results and detailed sensitivity analysis (single parameter simulation not reported here).

3.5 Development of 2015 foresight scenarios

The development of scenarios is based on the earlier approach by Alcamo et al. (1996), and consists of identifying driving forces (or drivers) likely to influence future production choices (cropping patterns) and farming practices. The group of expert is also mobilised to identify future trends for economic parameters determining farm production choices.

3.5.1 Driving forces identification and characterization

Twenty six driving forces were identified by the French and German expert group and gathered into seven categories:

[8] Even if we can not make a direct interpretation of the MOTAD model with the Arrow-Pratt coefficient of risk aversion. See Review Chapter (2).

1. agricultural market and policy. It includes the reform of the Common Agricultural Policy (CAP), World Trade Organisation (WTO) negotiations, European enlargement, the development of a demand for products of high quality, etc.;

2. other markets and economic policy evolution (land, labour and energy markets),

3. environmental policies (farming practices, cross-compliance, second pillar of the CAP, implementation of the Water Framework Directive, etc.);

4. the "natural" environment, in particular climate change (impact on crops and nitrate migration processes in soils) and proliferation of a corn parasite;

5. technological change (selected varieties, simplified farming practices, GMOs);

6. the evolution of social demand for organic farming and quality labels;

7. other socio-economical characteristics of the agricultural population (demography, concentration of farms, capital level etc.).

For each of the 26 drivers, experts were asked to assess and describe the most likely trend and the uncertainty of each. Whereas some of the changes are considered as almost certain, others will not necessarily occur significantly before 2015 (e.g. climate change). A prioritization of factors according to intensity of impact and uncertainty lead to the identification of six key driving forces that will be taken into consideration in the models for the 2015 simualtions. The six driving forces are described in the following paragraphs.

The 2003 CAP reform

The CAP reform (Luxemburg agreement of 2003) represents a major driving force likely to determine future evolution of cropping patterns, farm practices and the risk of nitrate leaching in the study area. The direct payment subsidy system introduced by the reform will significantly modify economic incentives in the farming sector in Europe. After the reform, each farmer will be allocated a fixed number of rights (expressed in hectares), each right being eligible for a fixed premium, which amount is independent from the crops cultivated. This decoupling of subsidies from production will not be implemented similarly in France and Germany (see Graveline et al. (2004b) for a detailed description). There are two major differences. First, while Germany has adopted a total decoupling system (Deutscher Bauerverband, 2003), France has decided to keep a 25% coupling system for main crops (75%

of the premium is fixed and 25% depends on the cultivated crop) (Ministère de l'agriculture de l'alimentation de la pêche et des affaires rurales, 2004). Secondly, in France, the amount of the fixed part of the premium is specific to each farmer and calculated on historical cropping patterns, whereas a regional average amount was defined in Germany, implying a subsidy increase for extensive farmers at the expenses of intensive farmers (a temporary decreasing compensation payment is however implemented and called top-up premiums). Overall, the reform will modify the relative profitability of crops and it could result in changes of cropping patterns, such as a decrease of area under corn (corn was benefiting from a premium higher than other cereals until 2003) if the effect of the new subsidy system is higher than the remaining relative benefit of corn compared to other crops.

The cornroot worm

Another major driving force identified is the risk of proliferation of the corn rootworm (*Dibrotica virgifera*) which has been observed for a few consecutive years and caused major damage to corn fields in the south of the upper Rhine valley (Hardt and Sundgau). The propagation of the parasite around Paris in France, in Eastern Europe and in the United States suggests that the parasite could spread in the upper Rhine valley, possibly resulting in a drastic reduction of corn cropping patterns. In a 10 000 ha safety area, corn has been reduced in 2003 by 70% due to both regulatory measures and self limitation by farmers. Although these significant measures have been adopted to keep the parasite development under control, experts consider that the risk of proliferation is real. Would the parasite spread in the entire Rhine valley, farmers would have to implement a three years corn crop rotation, implying a reduction of the corn area to a approximately 30 to 40% of the total arable area. This adjustment in cropping pattern would be probably spontaneously adopted by farmers after a few years of observed damages.

Energy price

If the oil price trend is confirmed, the profitability of energy-consuming crops could decrease, in particular crops requiring important mechanical operations, irrigation and drying (the case of corn). Fertilizer prices, which are strongly correlated to the price of energy, could also rise. This could induce farmers to reduce yield objectives and nitrogen supply, and, as a consequence reduce nitrate emissions. Also, an increase of oil price could generate a new demand for bio-fuel at an industrial and farm scale (development of raw oil on-farm productions), offering new cropping possibilities to farmers and an alternative to the corn-cereal specialisation.

The development of bioenergy crops

The price of energy could also lead to the development of increased biofuel and bioenergy demand. Two types of industries could emerge: the first one, in Baden only (because of national policies), consists of industrial production of bio-gas from corn; the second consists in producing raw vegetable oil from rape, either at farm level (autoconsumption) or at industrial scale. At farm level, farmers can produce their own fuel and use oilcakes as fodder for animals. The development of these crops will largely depend on economic policies (taxes and subsidies), legislation and the local development of the necessary transformation industry.

Price and taxes for irrigation water

In Alsace, where the area under irrigation is significant, the cost of water for farmers is very low. There are no taxes on water withdrawals in the aquifer (tax exemption) and the water is available only a few meters under the ground level which results in very low energetic costs. In Baden farmers must pay a tax called "Wasserpfennig" (i.e. the watercent). In France, a similar tax could be implemented (debate on water law) within the implementation of the Water Framework Directive that stipulates that Member States have to put incentive tariffs on water. This would lead to a reduction of the mean rentability of irrigated corn and vegetables and could favour the development of alternative crops.

European enlargement

The European Union enlargment may imply an increase of seasonal labour costs in Germany, where it is relatively low because of the possibility of hiring workers from Eastern Europe (Poland mainly) with no regulatory minimum salary (which is not the case in France where a minimum salary exists). The recent accession of these countries to the European Union will certainly lead, until 2015, to a progressive increase in salary levels. This will have repercussions on the seasonal labour market in Germany. Gross margins of vegetable crops will in consequence be reduced, perhaps leading to a reduction in these areas, which are today severely contaminated by nitrates.

The six driving forces described above correspond to parameters in the economical models that can be modified in order to carry out the simulations. Table 5.1 describes this correspondence between driving forces and parameters of the models.

Driving forces	**Parameter of economical models modified to simulate impact of driving forces**	**Concerned models**
CAP reform	Gross margins produced per area unity (€/ha)	F & G
	Upkeep cost for non productive land (set aside)	F & G
Cornroot worm	Rotation constraints represented by a lower limit for area under corn (in %)	F & G
Energy price	Farm gasoil price and other energy sources appearing in the technical itinerary (field works, irrigation and drying)	F & G
	Mineral fertilizer prices	F & G
European enlargement	Cost of seasonal labour force	G
Water price and taxes	Price and taxes on consumed water	F & G
Development of biofuels	Possibility to produce raw vegetable oil from rape and to produce agricultural fuel-oil	F & G
and bioenergy	Possibility of selling the corn production (silage corn practices) to a biogas plant	G

Table 3.4: Correspondance between driving forces and parameters of economical models. F: France/Alsace; G: Germany/Baden

3.5.2 Global change scenarios

Given that different assumptions can be made on the evolution of each of the six driving forces, the total number of scenarios resulting from a combination exercise can be significant. In order to reduce the number of scenarios to be simulated, three contrasting scenarios have been developed. Each scenario corresponds to a combination of assumptions which are internally consistent. A business as usual (BAU) scenario, representing the most plausible evolution of the economic, regulatory and natural environment has been constructed. Two other scenarios have been built on more extreme assumptions in order to cover a larger spectrum of futures and possibilities. These two scenarios have largely been inspired by the global emission scenarios proposed by the Intergovernmental Panel on Climate Change

(Intergovernmental Panel on Climate Change (IPCC), 2000). The underlying assumptions have been discussed within the expert group.

The BAU scenario assumes the following changes in agriculture driving forces. The corn root worm, which has been detected since 2003 in the area, extends over large areas, forcing farmers to increase crop rotations (area under corn cannot exceed 50% of the cultivable area). Energy prices and fuel oil are supposed to increase by 6% per year on average (2015 prices are twice those of 2003) and no financial compensation mechanism will be implemented by national governments. As a result of energy price growth, the price of fertilizer will increase by 1.5% per year. Due to European enlargement, temporary labour cost increases (+66% in twelve years), reducing the profitability of vine, fruit and vegetable crops in particular in Germany where a foreign labour force is significantly used for these crops. In France, the reform of the Water Act establishes a new water abstraction tax of 0.025 €/m3. In Germany, the tax called *Wasserpfennig* is maintained at its 2003 level (0.05 €/m3). In France as in Germany, farmers are allowed to produce bio-diesel (rape) on farm for their own use, but not for sale. The bio-gas industry will develop in Germany only with the possibility of selling the product locally.

The second scenario, A1 with reference to IPCC emission scenario A1, depicts a more liberal future. With this vision, agriculture development aims at maximising competitiveness in markets which tend to function without protectionist barriers and with a minimum of environmental constraints: taxes on water abstraction are suppressed in Germany and not introduced in France. The liberalization trend leads France to fully implement the decoupling principle promoted by the Common Agriculture Reform, which results in a change in crop gross margins and crop profitability. Energy price increases are compensated by a fiscal stabilisation mechanism and do not exceed respectively 40% and 68% in Germany and France. Significant technical means are mobilised by government agencies to fight against the corn root worm (pesticides sprayed from helicopters). The biofuel industry develops, representing new market opportunities for farmers.

The third scenario, inspired by the B2 IPCC emission scenario, corresponds to a vision of the future where agriculture evolves under the double pressure of increasing input prices (energy, fertilizer) and more stringent environmental constraints. Water abstraction taxes are established at the level of the BAU scenario. A tax on fertilizer is introduced and amounts to 0.15 €/kg in France and 0,26 €/kg in Germany. Due to high energy price and active government support to the bio-fuel industry, crops used for bio-fuel production represent a very attractive market. The proliferation of the corn root worm compels farmers to reduce the area under corn. Financial support is granted to fruit and vegetable farms to invest in machinery and compensate for the increase of temporary labour costs.

If the first scenario reflects the more likely evolution of driving forces within the limits of 2005 knowledge according the expert group, alternative scenarios follow less accepted logic. The scenarios help to evaluate the relative effect (with comparison with the 2003 reference and BAU scenario) of these types of global policy and economic evolutions on nitrate contamination. The B2 scenario is clearly an environmental orientation (corn root worm is not eliminated with the help of intensive pesticide use, water protection policies are implemented, no tax exemption and high energy prices induce a reduction in consumption) while the A1 scenario is more liberal and not concerned with the environment because government supports the energy price increase and no environmental policy is implemented.

All three scenarios as well as the reference scenario are quantitatively characterized with respect to single driving forces. This exercice is based on a detailed litterature review and completed and validated with expert consultation. Figure 3.5 details all the assumptions and values taken for each scenario.

3.6 Simulating the impact of global change scenarios

For each scenario, the economic models are used to simulate cropping patterns (area under each crop), input use (in particular fertilizer, energy, water) and total gross margin, simulated cropping patterns are then transmitted to the nitrate balance model and groundwater model for assessing the environmental consequences of the scenarios in terms of distributed nitrate concentration in the aquifer.

3.6.1 Impact of the 2003 CAP reform

To simulate the impact of the CAP reform, the price vector of the model is modified to take into account new subsidy values. Additional constraints are also inserted to take into account the decoupling principle and the conditions for premiums payments. These changes differ between German and French farm models to take into account CAP reform specific implementation. Simulation results show that crop choice is only slightly affected by the reform. In France nearly no changes in cropping patterns are observed, except for tobacco which disappears (reduction of 1400 ha) due to a drastic decrease in subsidy, and which is replaced by corn. Mineral nitrogen consumption and the estimated post harvest nitrogen

Horizon		Reference scenario 2003		BAU scenario 2015				A1 Scenario 2015				B2 Scenario 2015			
(driving forces) Impacted factors	Unity	BADEN	ALSACE	BADEN		ALSACE		BADEN		ALSACE		BADEN		ALSACE	
(GAP Reform) cf.(1) Gross margins cf.(3)		calculated for 2003	calculated for 2004	Total decoupling + single payments cf.(2) + modulation 5%		Partial decoupling (75%) + Single payements cf.(2) + modulation of 5%		*same BAU*		Total decoupling + single payments cf.(2) + modulation 5%		*same BAU*		Total decoupling + single payments cf.(2) + modulation 5%	
Respect of the "good agricultural and-environmental conditions"				interdiction to turn over permanent pastures; grass planting and diversification or humus balance cf.(4)		interdiction to turn over permanent pastures; grass planting and diversification or soil covering cf.(5)		*same BAU*		*same BAU*		*same BAU*		*same BAU*	
(Corn root worm) Maximum fraction of agricultural area occupied by corn	% UAA	-	-	spontanuous adaptation of farmers	50%*	spontanuous adaptation of farmers	50%*	no limitation	-	no limitation	-	Spontaneous three year rotations for corn	30%	Spontaneous three year rotations for corn	30%
(Energie price) Price of farm gasoil. Assumption : all on farm energy consumption is made by gasoil.	€/L gasoil	0,62 (of which 62% taxes)(a)	0,40 (of which 47% taxes) (b)	Increase of 100% (c)	1.24	Increase of 100% (c)	0.80	Gasoil price increase of 100% (before tax): +40%	0.87	Gasoil price increase of 100% (before tax): +68%	0.67	Increase of 200% of (incl. all tax) price to 2003	1.86	Increase of 200% of (incl. all tax) price to 2003	1.20
Price of mineral fertilizer (TTC) (the *HTT price is composed of 40% of energy cost)(g)*	€ /kg N	0,58 (of which 16% VAT) (d)	0,58 (of which 5,5% VAT) (e)	Increase due to the energetical cost of fertilizer price (before tax) (g)	0.66	Increase due to the energetical cost of fertilizer price (before tax) (g)	0.69	Increase due to the energetical cost of fertilizer price (before tax) (g)	0.66	Increase due to the energetical cost of fertilizer price (before tax) (g)	0.69	Increase due to the energetical cost of fertilizer price + Tax of 0,26 €	1.00	Increase due to the energetical cost of fertilizer price + Tax of 0,15 €	1.12
(European enlargment) Price of non permanent / seasonal labour	€ / hour	Price of foreign labour: 5,11 (d)	7,19 (f)	Labour price (national)	8,5*	Price of national labour force	7.19	Price of national labour force	8,5*	*No evolution*	7.19	Stable on 2003 level, in order to keep advantage of crops in the region	5.11	*No evolution*	7.19
(Price and taxes on consumed water) Price of consumed water	€ / m3	0,05 ('Wasser-pfennig')	0	*No evolution*	0.05	Taxe of 0.025€/m3 for a consumption of > 7000m3/year (h)	0.025	"Wasserpfennig" supression	0	No taxes or fees	0	*No evolution*	0.05	Tax of 0.025€/m3 for > 7000m3/year	0.025
(Development of bioenergies and contract crops) Possibility of crop selling for the production of biogaz	€ /ha	No "biogaz" industry to valorize corn		Corn sale (field) by farmer to the transformation plant	800	*No biogaz industry that develops*		*same tendency scenario*		*same tendency scenario*		*same tendency scenario*		*same tendency scenario*	
Possibilty of raw vegetable oil production	L d'huile / ha de colza	No vegetable oil industry to valorize rape		Transformation of rape in oil on the farm and valorising oilcakes	1072	Transformation of rape in oil on the farm and valorising oilcakes	1000								
Increased possibility (with regard to 2003) of contract crop production	% de plus / 2003	-		For brewery barley, industry rape, quality wheat	10%	*no foreseen development*									

Figure 3.5: Synthesis of the assumptions made for the three scenarios in France and Germany

Sources: *= according expert advice or working group ; (a) LEL and Statistisches Bundesamt ; (b) La Fiscalité de l'Energie -DGEMP-Ministère de l'Economie des Finances et de l'Industrie ; (c) between 2003 - 2006 an increase of 50% ; (d) from LEL : Landesanstalt zur Entwicklung der Landwirtschaft ; (e) from SCEES and study Ferti-mieux ARAA ; (f) INSEE ; (g) from UNIFA 2005 and www.econologie.fr; (h) water law project (2005). It is assumed that expected mean productions prices and yields remain constant unless a 1,5% per year yield increase for corn. Notes : (1) We assume that in 2015, the 2003 CAP reform will still apply even if in 2013 a new reform should be taken; (2) the direct payment (DP) compensate the supression of the reduction of the coupled payments. It is the product of the rights to payments times the payments per hectare. It is subject to the activation of rights. (3) prices of products and yields are assumed constant to the level of 2003 (except for corn that shows a yield increase of + 1,5%/year) ; the "carbone credit" is a subsidy of 45€/ha for energetic crops that are grown under contract not on regulatory fallows. (4) (i) all cropped areas have to be at least covered with vegetation that has to be ground or mulched when not harvested (ii) diversification :3 crops have to be present on the farm (15% at least per crop) (5) (i) at least 3% of the cereal and oilseed area and fallow has to be grown with grass (or grass strip) ; (ii) diversification: to have at least two families of crops (or 3 crops) or have intermediate winter cover crops (IWCC) residual content of the soil remains constant. Water consumption slightly decreases (-8%). These simulated evolutions are confirmed by observed changes in 2006 harvest (first year after CAP reform implementation) which showed nearly no changes in farmers choices. The impact of the CAP reform on farm income is much more significant, in particular in Germany where total gross margin reduction is close to 10% for certain farm types (-9% for large cereal oriented farms, -12% for milk oriented farms). The impact is less marked in France where corn oriented farms lose less than 2% of the total gross margin and milk farms lose 7%.

3.6.2 Global change scenarios

Simulated change in cropping patterns

Under the BAU (or tendency) scenarios, farmers diversify their cropping patterns and substitute 26% of the cultivated crops cultivated in the 2003 reference situation by different crops than in 2003. The overall usable farm area remains the same in all scenarios. The change is more important with the B2 scenario (41% of the land occupation will change) due to stronger assumptions than in the BAU scenario. Conversely, the A1 scenario induces a change of only 17% of agricultural land occupation. The cropping pattern corresponding to the three scenarios and the 2003 reference year are described in Figure 3.7.

In the baseline scenario, the area under corn decreases in the whole study zone (-24% of the total agricultural land) to the benefit of cereals (wheat and a small proportion of barley) and, slightly, to rape which is transformed in biofuel on the farm. Corn monoculture is no longer practiced and two to three year rotations (corn / wheat / rape) become more frequent in France, and are generalized in scenario B2. This is due to the expansion of the cornroot worm, the increase in the fuel oil price and, to a lesser extent, to increased fertilizer prices. For a few farm types, fertilizer tax contributes to this evolution (wheat replaces corn in a greater proportion). Livestock (mainly milk production) and crops with high added values (e.g. sugar beet) are not modified, except for market garden crops which disappear in response to the increased labour price (not in scenario B2) and tobacco which disappear partially due to the CAP reform.

Although the evolution is similar in Alsace and Baden, impacts are stronger in Alsace in terms of changes of cropping patterns (32% in Alsace against 11% in Baden of areas are concerned by changes in the BAU scenario). This is explained by the fact that Baden farms are more diversified then Alsatian ones where corn is largely dominant in 2003, and

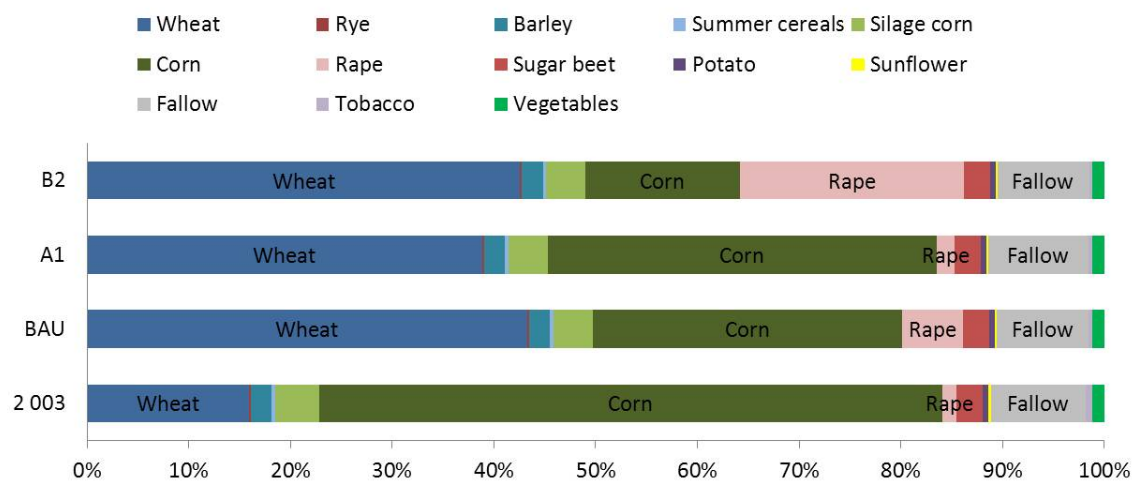


Figure 3.6: Distribution of total cultivated area per crop simulated with economic models - Alsace

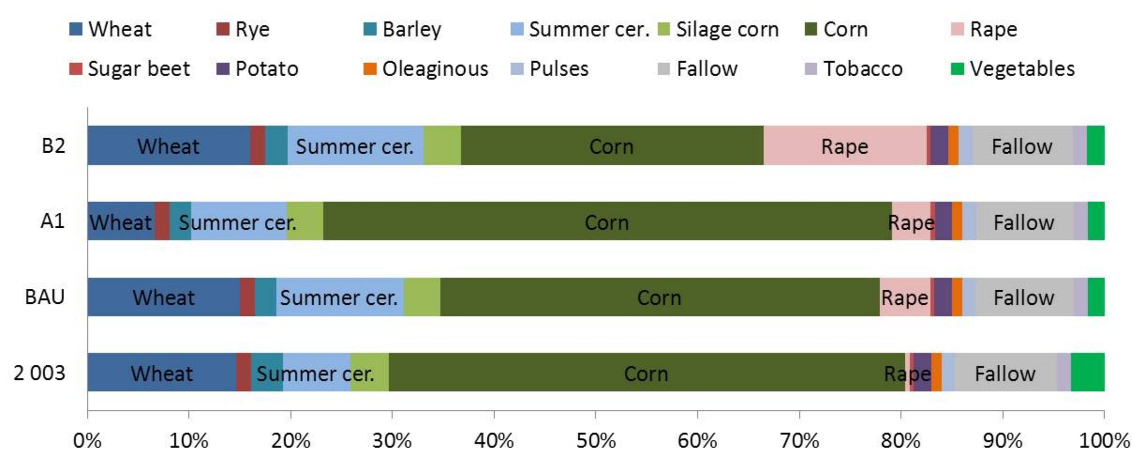


Figure 3.7: Distribution of total cultivated area per crop simulated with economic models - Baden

corn is the crop whose profitability is the most affected by the three scenarios. Diverse responses are also observed for the different farm types which are more or less sensitive to the simulated changes.

The A1 scenario turns out to induce less changes on the french side, even if its cropping pattern are close to those of the BAU scenario. In Baden, the A1 scenario shows an increase in corn areas to the expand of cereals.

The large development of rape (for raw oil production) in the B2 scenario (Alsace and Baden) is a direct response to increase of energy price that incite farmers to produce their own biofuel. Whatever the impact on nitrate contamination, it should be considered that this development would engender a reduction in greenhouse gas emissions, of about 8% reduction of the CO2 agricultural emissions.

	Ref 2 003	Baseline 2015	A1 2015	B2 2015
Wheat	39.0	+20.4%	+14.9%	+20.3%
Rye	1.3	-	-	-
Barley	5.9	-0.3%	-0.3%	-0.3%
Summer cereals	5.0	+1.6%	+0.8%	+1.8%
Silage corn	10.6	-0.4%	-0.4%	-0.4%
Corn	146.4	-24.4%	-15.2%	-39.4%
Rape	2.8	+4.6%	+1.2%	+19.5%
Sugar beet	5.1	-	-	-
Potato	2.2	-	-	-
Oleaginous/ Leguminous	2.0	-	-	-
Fallow	23.8	-0.2%	+0.4%	-0.2%
Tobacco	2.2	-0.3%	-0.3%	-0.3%
Vegetables	4.3	-0.4%	-0.4%	-0.4%

Table 3.5: Simulated evolution of the agricultural cropping pattern for the whole area (Alsace and Baden) in 1000 hectares and in % of the total area (250 495 ha) for the global change scenarios

Evolution of farming practices

The simulated changes also impact corn fertilizing practices. Alsatian farmers reduce the nitrogen application in response to fertilizer and energy price increase. This adaptation of practices is enabled by varying levels of nitrogen in the model.

In Baden, fertilizer reduction is lower than in Alsace, partly because fertilizer use in the 2003 reference situation is already lower than in Alsace. The different fertilizer practiced considered (i.e. that the model can choose) are different levels of fertilizer intensity use. Corn I refers to the less intensive practice and Corn III to the more intensive practice that is assumed to be the medium practice for all farmers in the reference. Fertilizer practices on corn are showed on Figure 3.8 for Alsace and Baden for all scenarios. In Alsace, the relative important reduction in nitrogen application on corn can be justified by the increase in energy price and of fertilizer price.

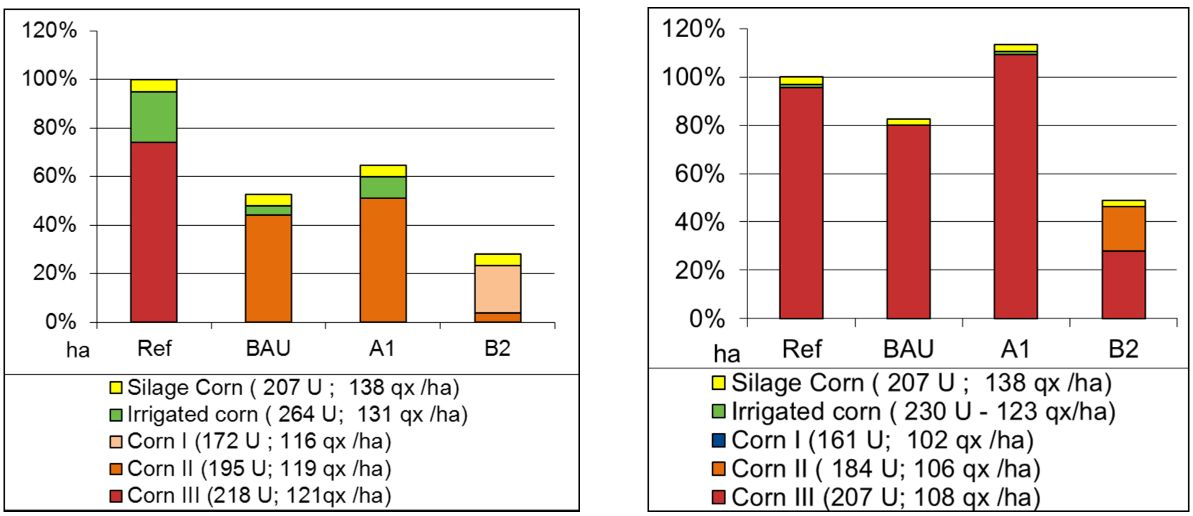


Figure 3.8: Percentage of area grown under each corn practice (100% refers to the total corn area grown under the 2003 reference situation). Left figure : Alsace; right figure: Baden. "172 U" refers to the dose in kg of equivalent nitrogen applied under each practice; "138 qx/ha" refers to the mean yield associated

Groundwater abstraction for irrigation (for corn, vegetables and tobacco) is also reduced by approximately 70% (50% in the A1 scenario and 80% in the B2 scenario). This is due to the decrease of the area under irrigated corn, vegetables and tobacco. Irrigation is reduced even more in Alsace where it was already more significant than in the Baden region in 2003. The area under irrigated corn is reduced and even disappears in the B2 scenario, along with tobacco (all scenarios). This induces a 6% reduction from aquifer withdrawals for the BAU scenario.

The future scenarios suggest a development of Intermediate Nitrate Trap Crops (INTC) due to the increase in area under winter cereals which enables winter and autumn INTC sowing. INTC area increases from 12% of the agricultural area (in 2003) to 40% (baseline scenario) in Alsace and from 20% to 26% in Baden. These results must be interpreted with caution, because economic data vary from one farmer to another, and, like most agro-environmental measures their implementation by farmers is often largely due to none financial factors and include some *hidden costs* (sensitivity to environmental aspects, acceptability).

Economic impact of scenarios on agriculture

The results per country and scenarios are given in Table 3.6. Overall, the revenue decreases in all three scenarios compared to the reference situation, because of the increase in energy prices and the modulation of CAP payments. In the BAU scenario, total revenue[9] decrease by 11% in Alsace. This decrease reaches 18% in the B2 scenario and 8% in the A1 scenario. Individual farm types are all affected differently (detailed in the following Chapter). We remark that taxes on water and fertilizer in B2 scenarios are only responsible for 6% of the total revenue decrease.

In Baden the revenue loss is more important: it reaches 27% in the BAU scenario, 25% in the B2 scenario and 14% in the A1 scenario. In A1, this is largely explained by the farm type D (cereal crops and vegetables) which stop the vegetables production and thus loose an important part of their revenues. In B2 the irrigated corn growers and multiple-jobs holder support the higher decrease in revenues (about -40%). The diversified farms that include vegetables production are not affected on this production because of the local supports to this industry. Taxes on water and fertilizers in B2 scenarios are only responsible for 12% of the revenue decrease.

The changes in value of total production[10] are slightly more important reflecting that some of the revenue losses are due to the increase in costs (energy price among others).[11] The B2 scenario in Alsace and the BAU and A1 in Baden turn to have significant impacts (more than 15% decrease) on the value of total production. Even if the remaining scenarios, changes are not overly important, it should not overshadow the crop specific value changes. Corn, for instance, has reduced a lot for the benefit of wheat and barley. This implies restructuring of transformation industries (agro-food and trade) which would have to be able to take on the cereal production (wheat and barley) and find markets for rape by-products (oil cakes for animal food or heating).

[9]the product of gross margins times cropping patterns
[10]the product of prices time yields
[11]the difference between revenues and value of total production here are the total costs of production

Note that a part of the reduction of marketable agricultural production is partially replaced by on farm production of autoconsummed biofuel.

	Ref 2003	BAU	A1	B2
Revenues				
Alsace	318.0	-11%	-8%	-18%
Baden	52.7	-27%	-14%	- 25%
Value of Production				
Alsace	468.5	-6%	-3%	-15%
Baden	111.1	-21%	-15%	- 4%

Table 3.6: Evolution of revenues (total gross margins) and of the value of total production in Baden and Alsace in respect with the reference situation (2003) given in Million € 2003

Long term impact on nitrate concentration

The consequences of the three global change scenarios were assessed using the chain of integrated models. The results from the economic farm models were extrapolated at the PRA level and used as input to the Stoffbilanz model. The results show that future nitrate average concentration in the aquifer will not significantly differ from one scenario to another in the short term. It is estimated at 19 mg/L for the baseline and A1 scenarios, and 19.5 for the B2 scenario. This can be explained by the long response time of the aquifer to surface pressures. See Table 3.7 and Figure 3.9. Differences are expected to increase in the long term: average concentration of 16 mg/L for baseline and A1, 18.2 mg/L for B2. The model also shows that the area where nitrate concentration exceeding the drinking water threshold value (50 mg/L) will fall from 17 000 ha in 2005 to around 4000 ha for the baseline and A1 scenarios and 6000 ha for the B2 scenario. Surprisingly, scenario B2, which is assumed to depict a world with more stringent environmental constraints, is also the worst scenario in terms of water pollution due to the increase in industrial crops used for producing bio fuels. This is largely due to the important positive (excess) nitrogen balance of rape. This would require further validation, before all concerning the nitrate emissions by rape that are large in our models (Stoffbilanz model) and that largely explains the higher impact in this scenario.

	Unit	2015[12]	2050 (simulated cropping patterns)			
		Ref	Ref	Baseline	A1	B2
Mean Nitrate concentration in the aquifer	mg/L	19,4	17,4	16,0 (-8%)	16,4 (-6%)	18,3 (+5%)
Area that exceeds NO3 threshold (50 mg/L)	ha	10 963	5 637	-38%	-31%	+5%

Table 3.7: Simulated evolution of nitrates concentration in the aquifer. The % are given by taking the 2050 reference. Source : LUBW (2006)

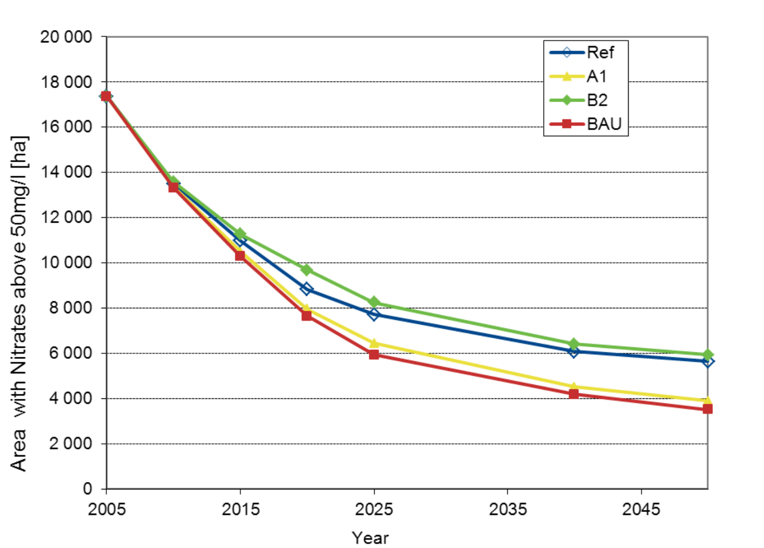


Figure 3.9: Simulated evolution of the area (in ha) where nitrate concentration exceeds 50 mg/L (adapted from LUBW, 2006).

3.7 Simulating the impact of price-based instruments

Although nitrate pollution trend seems to stabilise in the Upper Rhine valley aquifer, policy makers are increasingly aware that additional measures must be implemented to reach the objectives of the Water Framework Directive by 2015. We detail the instruments that have been implemented up to 2003 in Appendix 3.8. A survey of policies implemented in different countries has enabled to identify measures which could be implemented in the Upper Rhine valley (Graveline and Loubier, 2004). Economic tools such as fertilizer tax, nitrate emission quotas or the development of a market of tradable pollution rights (see Jensen et al. (2002)) have been implemented in certain countries or investigated in research study. For instance, different nitrogen tax systems have been implemented in Denmark, Norway and Sweden (see for instance Schou et al. (2000)). In the Netherlands, farmers are taxed according to the nitrogen surplus in their fields according to a system called MINAS (Minera Accounting System) and they can sign agreements to be financially compensated for the transfer of manure (MTAS : Manure transfert agreement system, see Berntsen et al. (2003)). However, the effectiveness of these measures might be site specific.

We tested two alternative taxes with the economic models: a tax on fertilizer application and a tax on post-harvest residue. The principle of the tax consists in increasing the cost of input use or putting a cost on input externality (in the case of nitrogen residu) to increase the optimal marginal benefit that will equate the marginal cost and, thus, reduce derived demand of input. Thus farm revenu will decrease.

Note that for these experiences we do not implement the whole modeling chain and worked only with the economic models. Here we use standard values per hectare, per soil and per crop from the Schalvo program as a proxy to post-harvest nitrogen residu, i.e. nitrate impact on groundwater, which is directly calculated from the cropping pattern results. The calculation is the same as the prior potential of nitrate leaching per farm.

Tax on fertilizer use

A first series of simulation were conducted to assess the impact of a tax that would be charged on fertilizer use per quantity in kilogram of nitrogen. The simulations presented below correspond to the typical C1 corn oriented farm. In the reference situation (2003), the farm is mainly growing irrigated corn (71 ha) and wheat (6 ha).

The simulation in Figure 3.10 shows that, with the 2003 economic environment (before CAP reform, low energy prices), C1 type farmers would not change their cropping pattern significantly until the tax reaches 1 €/kg. When this level of tax is reached, the tax becomes effective and farmers reduce the level of corn fertilisation. When the tax reaches 1.75 €/kg, the area under corn drops to about half of its initial level and is replaced by cereals (wheat). With an additional increase of the tax (2€/ kg), farmers reduce fertilisation to the lowest fertilisation level on corn.

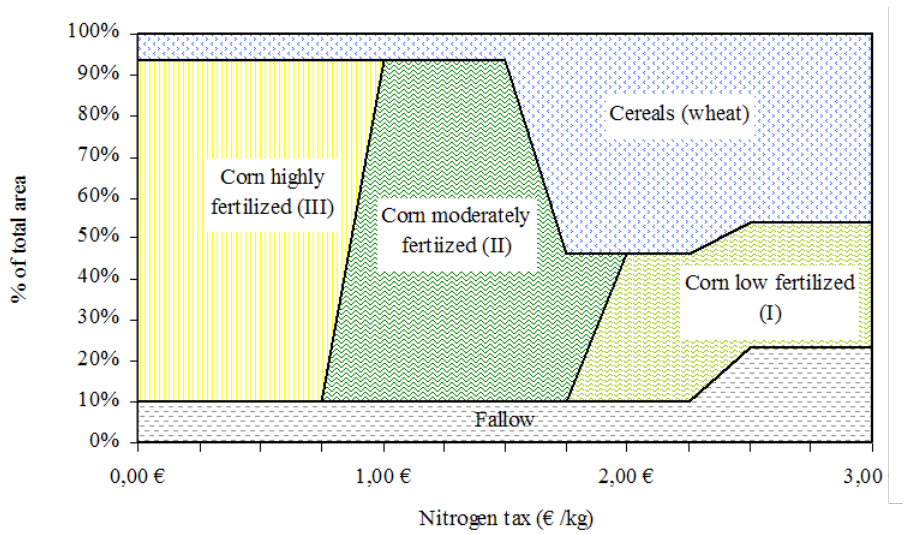


Figure 3.10: Simulation of the evolution of cropping pattern for various levels of nitrogen tax for farm type C1 in the reference situation (2003)

Figure 3.11 shows the evolution of fertilizer use associated to changes in cropping patterns and fertilizer use practices, as well as the impact on post harvest nitrogen residual in soils for C1 type. With a tax of 3€/kg, the total fertilizer use drops at about 50% of the initial level and the total farm income is reduced by half. This can be characterized as a none acceptable level from a policy perspective. To reduce the income effect of the tax, a marginal tax system could be designed, where farmers would only be taxed at high level for fertilizer used above a given threshold, considered as good practice.

Tax on nitrogen post harvest residual

We then simulated the impact of a tax that would be proportional to the average post harvest nitrogen residual at the farm level. With this system, inspired from the practical

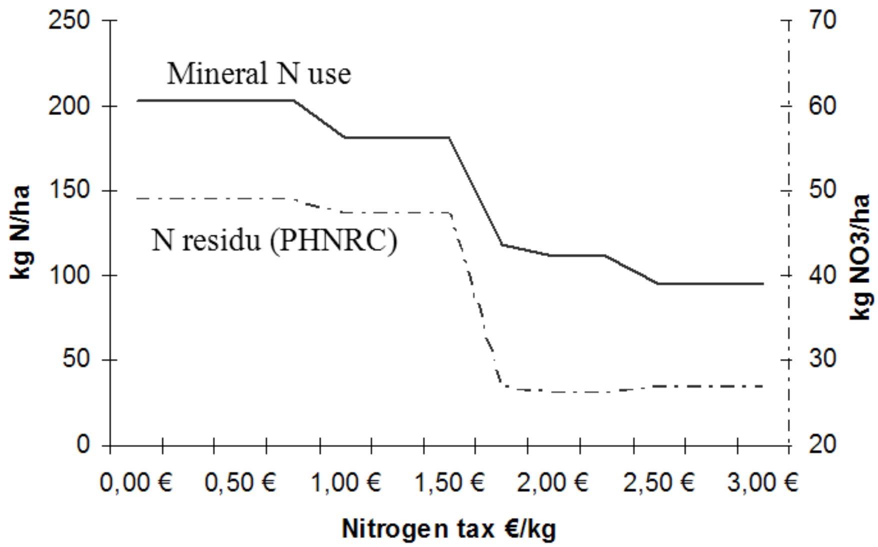


Figure 3.11: Evolution of post harvest nitrogen residual content of the soil with various levels of nitrogen tax for C1 and C2 farms

experience of the German SchALVO program and from theory (see e.g. Spaeter and Verchère (2004)), farmers are taxed on the basis of the actual impact of their activity and not on the quantity of fertilizer they use. This implies that soils analysis are carried out every year to estimate actual nitrogen residuals for a number of fields representative of the farms, entailing much higher transaction costs than with a simple tax on fertilizer use. The simulation results show that the tax becomes effective after 3 €/kg of residual per hectare for farms of type C1 where corn is partly replaced with wheat. The effect of the tax is different for farms of type C2, which start reducing fertilizer use for corn crops after the tax exceeds 1 €/kg of residual. This highlights that the effectiveness of this type of tax may differ significantly between farm types but also soils. The tax also has a strong impact on income, which could be mitigated through the definition of a threshold value below which the tax is not charged (for instance 30 kg/ha considered as the unavoidable nitrogen loss occurring with good practices).

3.8 Conclusion and perspectives

From a policy perspective, the simulations presented above clearly show that groundwater improvement which has been observed between 1997 and 2003 should continue at a rate that will change to reflect global assumptions. Surprisingly, the B2 scenario, which represents a future where CO_2 emission decreases, leads to the worst situation in terms of nitrate concentration. This result highlights how one type of environmental policy (here green house warming control) may negatively impact another policy (groundwater protection). This statement clearly calls for more environmental integration when assessing the impact of projects and policies. Assessments should include various criteria and look at the different environmental effects of scenarios considered, i.e. on air, water, biodiversity, landscape, etc. This could help identifying possible competitions or synergies between different environmental policies.

The results also show that the 2003 CAP reform is not likely to result in a significant reduction of the potential of nitrate diffuse pollution by farming. The simulation of more complex scenarios accounting for different economic and environmental changes suggest that nitrate contamination should progressively decrease. The potential offered by environmental taxes as a tool to reduce contamination is also explored through economic simulations. The results obtained show that the tax has to be set at a relatively high level to be effective, and this is probably prohibitive from an economical point of view if we would account for the cost supported by farms and agro-food industry.[13]

From a methodological perspective, the integrated modeling approach presented has proven to be efficient to simulate the impact of contrasting global change scenarios. In its philosophy, the approach aims more at exploring possible futures than forecasting what will actually take place in the coming decades. The use of models is an interesting approach to integrate assumptions made by experts, to assess their consequences and construct a shared vision of plausible futures. The development of several scenario variants is also considered as one way to account for uncertainties related to global change evolutions, such as unpredictable changes in world energy markets. The chain of models has also be used to simulate the impact of alternative management options (actions) that could be implemented to alter expected trends that are not presented here. This includes, for instance, simulating the impact of various forms and levels of subsidies for specific practices, including organic farming

[13]the implied social benefit could be calculated and compared to estimated benefits of improved water quality.

and possible subsidies for agro-environmental measures. The economic model developed here does not seem to be adapted to represent the bahavior of farming in respect to the adoption of specific management measures (as detailed in Appendix 6.8) except the price based instruments such as a fertilizer tax. The reasons are that the farm typology approach prevents from considering the diversity of farms within a type that could be necessary to assess correctly the adoption level based on different costs (including non marketable costs i.e. benefits such as the individual will to implement less extensive practices). A connected reason is that the determinants of the adoption of these practices are not very well known and as such can not be appropriately be integrated in the model specification.

The methodological approach presented here also has some caveats and limitations which must be stressed. Firstly, the extrapolation of the results obtained with modeling a limited number of real farms to the entire sector (23,000 farms) generates a bias which should be fully considered. Secondly, LP models are not able to account for the possible changes of farm structure, they assume that farm assets and constraints remain constant over time; in reality, the changes provoked by the CAP reform for instance might lead to the concentration of the sector, the specialisation of some farms; the typology elaborated in this project being static by nature, the methodology does not allow to describe the dynamics of farming systems and account for instance in structural changes of farms. However, in the present setting with a medium term horizon (10 years) this is not a considerable problem as farms can be assumed to show a certain inertia. The regional modeling is one solution to avoid this problem, because farm level and as such farm structure is not anymore considered and allows implicitely for farm restructuring. We will develop this type of assumption in Chapter 5.

Appendix

Groundwater protection policies in Alsace and Baden-Württemberg

A variety of measures aiming at modifying farming practices have been implemented on both sides of the Rhine to reduce and control nitrate contamination. However, the regulatory i.e. quantity based instruments are by far the more frequent.

The first group of regulatory measures ensues from EU regulations and in particular from the Nitrate Directive and from the Integrated Pollution Prevention and Control Directive (IPPC) (constraints related to manure storage). Concerning the Nitrate Directive, reference farming practices have been defined by Government agencies in collaboration with professional organization (in Alsace) or with the Extension Services (in Baden Württemberg) and they are imposed to farmers located within vulnerable areas. Constraints imposed to farmers are related to dates of land preparation or fertilizing, maximum quantities of fertilizers allowed and cultivation of autumn cover crops (nitrate sink). Constraints are relatively more stringent in Baden Württemberg than in Alsace. And on both sides of the Rhine, these regulatory measures are accompanied by information and training programs, called Ferti-mieux projects in France and Nitrate Information Services (NID) in Baden-Württemberg.

Other measures are related to the implementation of the environmental pillar of the Common Agricultural Policy. In Alsace, farmers are offered the possibility to sign 5 years Sustainable Agriculture Contracts (CAD) with Agriculture Government Agency (DDAF) in which they commit to adopt specific farming practices (8 type of CAD related to nitrate pollution reduction) against a financial compensation ranging between 91 and 374 €/ha (see Graveline and Loubier (2004)). In Baden Württemberg, a similar system is implemented (MEKA), farmers are entitled to select environmental friendly practices within a list of 30 measures, each one opening financial compensation rights (possibility to cumulate subsidies). Additional subsidy programs are implemented in Alsace and Baden Wurttemberg to encourage investment in manure storage equipment for instance or the conservation of grassland (subsidies granted by Region Alsace and Water Agency in Alsace).

A third type of measures aims at modifying farming practices in Drinking Water Protected Areas through financial incentives dedicated to farmers. In Alsace, such measures are implemented on a voluntary basis and they are formalized by contracts between farmers who commit to follow certain practices and Drinking Water Utilities who pay a compensation; the technical and the financial aspects of the agreements are determined by the Chamber of Agriculture. The authorities have gone one step further in Baden Württemberg by imposing that specific farming practices be followed in all protected areas called SchALVO : "Schutzgebiets- und Ausgleichsverordnung". Farmers used to be financially compensated during the first years of the program which was initiated in 1988 but the subsidy has been removed and farmers are now charged with a financial penalty if the residual nitrogen content of the soil exceeds a certain threshold value. This is a price based instrument similar to a tax. Since the SchALVO program applies to all drinking water protected areas, and given that these areas are much larger than their equivalent in France, its impact on groundwater quality is significantly higher than in Alsace. For a detailed description of the situation in Alsace, see Bosc et al. (2005).

Typology of farms: number of farms and usable agricultural area

ALSACE	total	C1	C2	C3	C4	D1	DG	DS	H	L1	L2	B1	B2	O	V1	V2	M
Nb of Farms	100%	5,9	3	0,6	34,3	5	0,9	0,9	2	2,4	3,1	0,8	2,3	0,3	26,7	11,2	0,8
Area	100	21	9,7	2,1	21	12	1,6	2,1	0,1	5,6	9,5	2,1	4,39	0,7	2,3	6	0,1
BADEN	total	C1/C2	C3	C4	C5	L1	B1	B2	D2-S	T p	VD	D1-M	other				
Nb of Farms	100%	4,9	4,1	26,7	10,4	0,6	0,5	0,4	0,4	1,9	14,5	2,9	34				
Area	100%	17	13,8	10,7	22,5	1,8	1,6	1,6	0,7	0,7	8,2	4,9	19,1				

Table 3.8: Share of farms and area within each farm type (Alsace and Baden regions)

Farm typology description and distribution of french farms accross types and PRAs.

Five cereals oriented farm types (C1, C2, C3, C4 and C5), differing in size, level of diversification and intensification, represent respectively 64% and 54% of the total arable area in Baden and Alsace region respectively. Farms C1 and C2 are large production units (80 ha on average in France, and 102 ha in Germany) specialised in corn production (74% - 62% of the cultivated area), other cereals representing less than 10% of the cropped area. The French type C1 has a significant irrigated area whereas C2 is mainly growing rainfed corn. No distinction is made between C1 and C2 in Germany (very little irrigated area). Farm type C3 is composed of large production units (95 ha) which diversify their production with cereals (36% Alsace, 27% Baden) and other crops such as rape, sugar-beet, oilseeds, etc. (22% in Alsace, 5% in Baden). This type covers a larger area in Baden (4% of total agricultural area) than in Alsace (1%). Farm type C4 is composed of very small part-time production units i.e. multiple-jobs holders (15 ha in Alsace, 12 ha in Germany) which represent 27% and 34% of the total farm sample in Baden and Alsace. In Baden, farmers of this type grow more cereals than corn (respectively 31% and 27% of the total area) whereas French farmers are specialised in corn (67% - with only 15% of cereals). Farm type C5, which is specific to Baden region, is also specialised in corn and cereals (49% and 15% of its area) but it derives a significant share of its income from intensive special crops : vegetables cover 4% of its area, asparagus 3% and tobacco and other perennial crops 6% (orchards, vines). This type does not exist in Alsace, due to the difference in labour legislation (no minimum wages in Germany for temporary labour which is widely used for intensive special crops). In general, all these types (C1 to C5) have a much larger area under grassland in Germany than in France (23% for C3, 13% for C1/C2 in Baden).

Farm type D1 (D1-M in Germany) is composed of medium size diversified farms (50 ha on average) cultivating a significant area of high added value crops such as sugar-beet, hops, tobacco on a significant area. German farms are much more diversified than the French ones, probably due to the difference in labour legislation: special crops represent 14% of the group area in Alsace and 62% in Germany (53% of vegetables, 3% of vine, 3% orchard, 3% of berries). Corn only occupies 30% of the area in Baden and 67% in Alsace. Farm types M and H, which are specific to Alsace, are also specialised in vegetable (M) and horticulture (H) production but unlike their German counterpart (D1-M), they operate very small areas (4 and 2 ha). These farms, which represent a very small total area (0,8 and 0,1% of the total area in Alsace) are not analyzed.

Farm type L1 and L2, specialised in milk production, only represent 5% of the sample in Alsace and 1% in Germany (covering 15% and 2% of the total agricultural area in Alsace and Germany). In Alsace L1 are more intensive than L2 (respectively 0,7 and 0,4 milk cows per ha), most of the area being used for fodder production. In Baden, only one type was identified (L, 0,76 cows per ha). Grassland represents 25% of the area in Alsace and 40% in Baden. Winter nitrogen trap crops are cultivated in 28% of the area in Alsace, probably as a response to the regulatory constraints related to manure spreading.

Farms of types B1 and B2 are specialised in beef production, B1 being more intensive than B2 which operates more area than what is strictly needed for fodder production. These farms are even fewer than the milk production oriented farms, they hardly represent 6,5% and 4% of the total area in Baden and Alsace. Overall, German farms operate more grassland than their French counterpart (respectively 40% and 30%). French farms also grow more corn (24 / 37% of the area of B1 / B2 in Alsace against 13 and 18% in Baden).

Farms of types V1, V2 and VD mainly rely on vine production (Alsace) or vine and orchard (Baden). They represent very large groups (38% of the farms in Alsace, 14% in Baden) but a moderate percentage of the total area (8%). Type V1 is more diversified than V2, farms of this group cultivates cereals (9% of its area) and corn (24%), the total representing 3% of the total cereal and corn area of the region.

Finally, a few marginal farms types specialised in animal production have been identified: sheep breeding (type O, Alsace), pig production (DS, D2S) and poultry farms (DG).

The following table gives the frequency of farms per PRA, it has been used for extrapolation of farm scale results at the PRA level.

Farm	Bas-Rhin			Haut-Rhin				Total	Share
Types	Plaine	Ried	Colline	Plaine	Ried	Colline	Hardt	farms	
C1	4	54	0	131	13	4	147	353	5%
C2	124	65	33	21	5	0	0	248	3%
C4	1 271	471	516	278	78	15	296	2 925	37%
D1	288	55	70	31	4	10	6	464	6%
L	219	68	316	33	15	0	0	651	8%
V2	99	5	1 304	146	0	1 642	0	3 196	41%
Total	2 005	718	2 239	640	115	1 671	449	7 837	100%
Share	26%	9%	29%	8%	1%	21%	6%		

Table 3.9: Number of farms per type and per PRA

Data on prices and yields variability

The following data has been used to characterize the Mean Absolut Deviation.

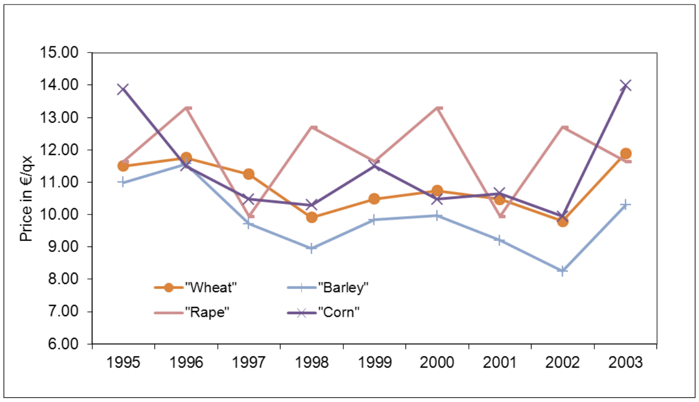


Figure 3.12: Product prices series for main crop production in Alsace

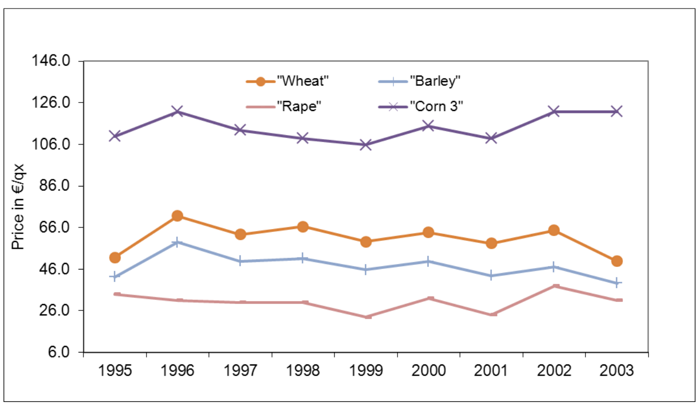


Figure 3.13: Yield series for main crop production in Alsace

Appendix: Agronomic response of yield to nitrogen in Alsace

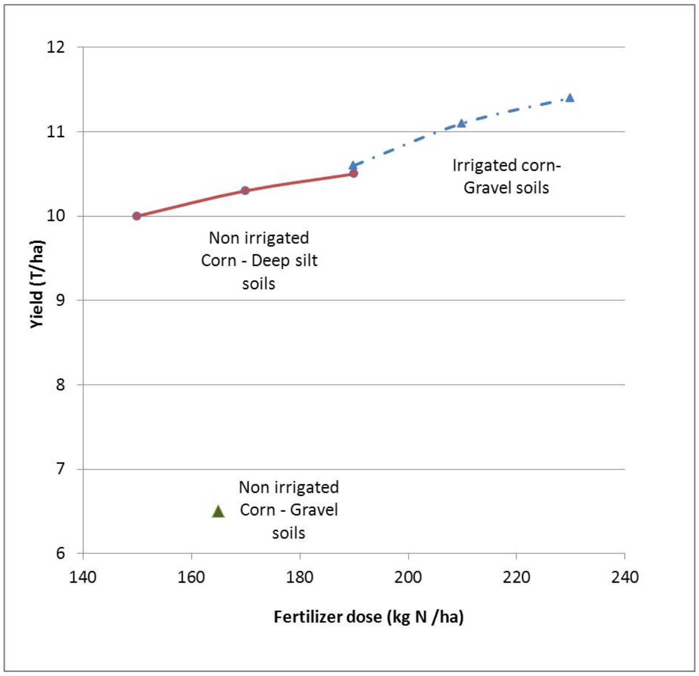


Figure 3.14: Agronomic response of yield to nitrogen in Alsace

Chapter 4

Impact of farming on water resources: assessing uncertainty with Monte Carlo simulations in a global change context.

[1]

[1]This chapter is adapted from an article which I wrote with Sébastien Loubier, Guy Gleyses and Jean-Daniel Rinaudo that has been published in Agricultural Systems in 2012.

4.1 Introduction

Various methods have been put to use to predict how pressures of agricultural origin will evolve and how they will affect water resources. The method based on extrapolating past trends, has often been used by river basin management authorities because it is easily implemented. Some applications of this method require complex statistical tools (Rinaudo et al., 2005) or are combined with the DPSIR (Driver, Pressure, State, Impact, Response) method (Bouisse, 2006). More complex methodological approaches have also been used in projects involving scientific research teams. These are often modeling approaches that combine coupled biophysical and economic models as discussed in Chapter 3 or integrated hydro-economic models (Pena-Haro et al., 2009).

One of the main difficulties inherent in building up scenarios of agricultural evolution and in representing the pressures generated on water resources by this evolution, is how to handle uncertainty: pressures on water resources (water abstraction and diffuse pollution) are highly dependent on the crops' and farming practices' choices, which depend themselves on the economic context and on the environment (water resources for instance). Indeed, it is clear that the context can change, especially as regards prices for agricultural products (Persillet, 2009), public subsidies (Common Agricultural Policy - CAP reforms), prices for essential inputs such as energy, and climatic conditions.

Several ex-ante policy analysis have therefore been focusing on the evolution of the agricultural sector. Most of these studies handle uncertainty by using only a limited number of contrasted scenarios for change in the economic environment. This methodological choice necessarily disregards not only extreme hypotheses, but also their action when combined. Yet when there is no ex-ante knowledge of probability densities in foresight scenarios, there is no way of knowing whether these extreme conditions may, or not, plausible future situations that public policy makers would need to consider before defining action programmes to implement the Water Framework Directive. The question of taking uncertainty into account in environmental impact assessment studies emerged in the 1980s, and is nevertheless rarely extended to methodologies (Payraudeau et al., 2005). For example, Gibbons et al. (2006) developed a methodology aiming at modeling the bio-physical uncertainty associated to greenhouse gas emission at the farm level. The present work aims at suggesting a method involving Monte Carlo simulations which enables to explore the impact of economic uncertainty on agriculture and its environmental pressures on water with linear programming (LP) models. The Monte Carlo approach builds on generating a large number of very different scenario alternatives, by allowing extreme but realistic model input parameter values to be randomly selected.

We used this method to illustrate the diversity of results within each scenario and to provide elements to quantify the probability of not achieving the WFDs' environmental objectives. This chapter describes the implementation of this method with two concrete examples of economic modeling of agriculture on the scale of two different French regions, Alsace in eastern France (Chapter 3 case study), and the Neste river system in the Midi-Pyrénées region in southwest France. These are of particular interest as agriculture in both regions exerts significant pressure, in terms of quantity (Neste) or in terms of quality (Alsace). The environmental pressures considered here are (i) water abstraction i.e. quantity issues for the Neste case study and (ii) groundwater diffuse pollution through nitrate leaching for the Alsace case study. In this latter study, the indicator used is a post-harvest nitrate residue (PHNR), corresponding to the nitrate contents left in the root zone at the end of the cropping period. The remainder of this chapter is broken down into five parts. The first one describes the modeling approach used to assess the environmental and economic impacts of global change scenarios. The second part describes the scenarios and the main factors of uncertainty taken into account to simulate the evolution of agriculture. The third part analyses the results of the simulations, highlighting the different scales considered. The last part discusses the results and interest of the approach.

4.2 Materials and methods

Without recalling here the state-of-the-art of the approaches which implement LP in a perspective of environmental impact assessment, we note that none of these studies analyse the uncertainty associated with the factors that determine change in agriculture. The methodology described in this chapter aims to fill this gap and is set out in the next section.

4.2.1 Microeconomic farm models for Alsace and Neste

Microeconomic models were developed and calibrated for different farm types in Alsace and in Neste for the reference situation in 2003 following the same methodology implemented in Chapter 3. The models used for Alsace are the same as the ones presented in Chapter 3. Neste models are described in detail by Gleyses (2006) and in Appendix. The main constraints are the limited resources (land, water and manpower in Neste). The MOTAD (Minimization of total absolute deviation) model has been chosen to integrate the variability of annual crop water requirement in Neste i.e. to represent the risk of not being able to satisfy the water needs according to availability. Here, as opposed to alsacian models, risk is on the constraint and not anymore on the objective function to represent variation on the water resource availability. This is justified by the fact that the water resource concerned is a surface water resource which is very variable and whose availability greatly varies with climatic conditions and reservoirs. The model used for the Neste is the following:

$$\max_{x_i \geq 0} \Pi = \sum_i x_i \left(p_i y_i + CP_i - c_i\right)$$

$$\text{subject to} \quad \begin{cases} \sum_i x_i \leq b_{land} \quad [\lambda_{land}] \\ \\ \sum_i \left(\bar{a}_{i,water} + \phi\sqrt{MAD_{i,water}}\right) x_i \leq b_{water} \; [\lambda_{water}] \end{cases} \tag{4.1}$$

with $MAD_{i,water} = F\left[\frac{1}{T}\sum_t (a_{i,water,t} - \bar{a}_i)^2\right]$
and $F = \frac{2}{T}\sqrt{\frac{(T-k+1)(T+1)\pi}{2T(T-1-k)}}$, the Fischer coefficient.

Where i represents the activity (for the Neste case study, crops only) and the irrigation or fertilizing practice, x_i the area of activities i within the farm, p_i the unit price for the product of each activity, y_i the yield or unit production of activity i, CP_i the CAP premium submitted to producing activity i (in the reference situation, the CAP premium is 42 €/ha higher for all irrigated cereals including corn, pulses and soybeans compared to the same rain-fed crops in Neste, and 65 €/ha higher for corn only in Alsace), c_i the cost of the variable factors in the activity. The direct (decoupled) payment is independent of the farmer's choice of cropping pattern and is not in the optimization problem but integrated in total gross margins. b_j is the available quantity of resource j (land and water) and $\bar{a}_{i,water}$ the Leontief coefficient or mean water application rate per crop. $MAD_{water,i}$ is the Mean Absolute Deviation of water needs per unit crop in the Neste model. This reflects the annual variation of water needs according weather. During dry years, farmers are not able to provide the crop water requirement because of the water availability constraint (equal for all years). The water consumption is then equal to the water availability: the constraint is binding and the farmer faces a yield drop. During wet years, crop water requirement is lower than the average water requirement and the water availability constraint is not binding (see Appendix for data). ϕ is the risk aversion coefficient. In addition to the limited resources constraints (land and water), other constraints related to crop rotation, organisation and regulation are considered and necessary for calibration (as detailed in Chapter 3 for the alsacian models).

The constraints on water and nitrogen use which are significant in the environmental impact of the agricultural production have been thoroughly detailed in the model. As shown in equation 4.1, there is one constraint in the Neste model which integrates the variability of water needs per irrigated crop. The variability is represented with the $MAD_{water,i}$ parameter which is calculated with a 24-year crop specific water requirement time series (see Appendix for details). Depending on the risk aversion (ϕ) of the farm type, the variability of water needs has more or less impact on cropping decisions. Also, the response functions of yields to input levels (nitrogen and water) are introduced discretely into the models (see Chapter 1 for Alsace and Appendix for Neste data). For the Neste basin, several different technical management options were identified for corn and soybean crops, corresponding to five levels of water input for corn and four for soybeans, which range from 50 to 100% of the plants agronomical needs.

Both models produce environmental impact output variables which are (i) the water consumption and irrigation intensity in the Neste model and (ii) an indicator for nitrate loss in the Alsace model, expressed as the *post-harvest nitrate residue* (PHNR) which is a proxy to nitrate pollution of groundwater from agriculture (see Chapter 1 for calculation and Appendix 4.5 for the values taken from Schalwo data).

4.2.2 Taking account for uncertainty in the scenarios

Both Alsacian and Neste models were used to simulate the impacts of different scenarios and different variants of these scenarios. The scenario build-up process is similar to the one developed by Abildtrup et al. (2006) and in the Chapter 3. The main difference with scenarios developed in Chapter 3 is that they were defined as to converge with scenarios defined by INRA at national scale (Jez et al., 2007) and others defined at European scale (Henseler et al., 2009). The specific regional characteristics in terms of public policies or physical constraints are also integrated in the scenarios. The last stage focuses on characterizing uncertainty related to the driving forces. Uncertainty can be studied for parameters of all types and must be considered at the very least for parameters whose values are uncertain, be the uncertainty biophysical (dependent on a biophysical process, e.g. greenhouse gas emissions, see Gibbons et al. (2006)) or of a micro- or macro-economic nature (e.g. producer prices). Even if uncertainty is inherent to the evolution process and per se not predictable, the uncertainty range depends on how assumptions on parameters values were made (expert knowledge, observations, measurements, etc.) (Dubus et al., 2003). The Monte Carlo analysis is used to assess uncertainty for biophysical parameters (Huijbregts et al., 2000) and biological parameters (Chen, 1996). It involves generating a large number of very different scenarios, simulating their economic and environmental impacts and performing statistical analyses of the simulation results. Lo et al. (2005) have shown that integrating uncertainty through a Monte Carlo analysis in a Life Cycle Assessment produces results which offer a more relevant support for decision-making.

In this study, as the value of some economic parameters was uncertain, Monte-Carlo simulations were implemented in order to explore uncertainty. Assumptions were made on cause and effect relationships for some of them and on the range of uncertainty, as recommended by Mahmoud et al. (2009).

4.2.3 Running the models

The farm-type models were run with the Micro Linear Programming solver developed by INRA, which uses the Simplex algorithm through a Microsoft Excel interface. Computer programming for the selection of random values and simulations was developed with Visual Basic (Microsoft Excel). After choosing one of the scenarios, the generator makes a random selection of parameters within a range of values compatible with the generic scenario. Two hundred repeats are performed for each scenario and the model runs for each farm type, the three scenarios and the 200 repeats. The results of each simulation are stored in a database for subsequent processing. The processing comprises the aggregation phase which consists in summing the products of the indicator value per farm type by the farm-type population (i.e. the number of farms classified per type). As such, the results can be contemplated at the regional scale. Figure 4.1 summarizes the models operation.

4.2.4 Description of the case studies

The irrigated Neste system in the Midi-Pyrénées region is a river system which is replenished with dam water. The main crops, covering 44% of the total usable farm area, are cereals

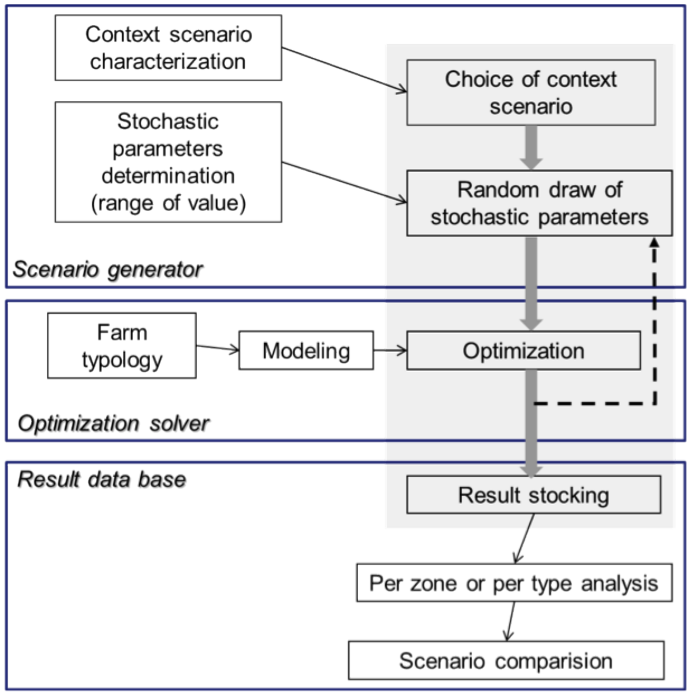


Figure 4.1: Architecture of the model

(soft wheat, corn and durum wheat), followed by oilseed and fodder crops, in almost equal proportions. One third of the farms (3360 in 2003) irrigate part of their crops. We consider these farms only since we focus on water consumption. These farms grow a total of 80 000 ha of irrigated crops including 68% of corn, followed by soybeans and pulses. Special crops (vegetable, fruit, etc.) cover less than 1% of the irrigated area. Within these farms, 90% of corn and 85% of soybeans are irrigated. Eleven types were considered for modeling. Details on these types are given in Appendix 1.

The second case study is the Alsace region as a whole and corresponds to the same case as in Chapter 3. The same six types of farms were modeled (C1, C2, C4, D1, L and V2), they represent around 80% of the usable farm area and of the pollution emitted by farming (slight adjustment compared to Chapter 3).

4.2.5 Selected scenarios

Three scenarios of change in the agricultural economic and environmental context were established. They are largely inspired from those described in Chapter 3 with, nevertheless, some adaptations mainly due to the publishing of INRA's *Prospective Agriculture 2013* in between.

The business-as-usual (BAU) scenario

This is an intermediate scenario which is similar to Le trot in INRA's Prospective Agriculture 2013. In this scenario, international WTO negotiations have resulted in a moderate agreement and the CAP has barely been amended: full decoupling except for livestock farmers, a slight increase in dairy quotas, fallows kept compulsory except when replaced by bioenergy crops. Livestock farmers, who can produce their own rapeseed cake, are allowed to produce unrefined vegetable fuel oil for their own use. Economic growth continues, with significant increases in fuel and input prices and, to a lesser extent, cereal and oilseed prices. Similarly, meat and milk prices have also moderately increased. Regulations on leaf beetle control limit the area grown with corn to 50% of the usable area of each farm in Alsace.

The liberal scenario

This liberal scenario is drawn from the A2 scenario developed by the Intergovernmental Panel on Climate Change (IPCC), the Le "galop" (gallop) scenario developed by INRA in its Prospective Agriculture 2013 study (Jez et al., 2007) and the Full Liberalisation scenario presented by Henseler et al. (2009). The assumption in this scenario is a liberal approach in a policy context aiming for maximum growth and minimum market regulation (some protective sectorial policies are removed). The EU is pursuing a CAP reform process resulting in a full decoupling and a 35%-reduction in direct payments. This accelerated growth causes tension in prices for agricultural raw materials and higher prices for fuel and inputs (fertilizer, drying costs) and a steep increase in cereal and oilseed prices, with bioenergy production competing with food production. Prices for dairy products and meat are also rising but less steeply than for crops. Environmental concerns are of secondary importance. The ban on ploughing grasslands, the tax rebate on agricultural fuel and compulsory fallowing have been removed, dairy quotas are virtually nonexistent and the tax on irrigation water abstraction has been multiplied by 4 (no support to agriculture was powerful enough to reject this water conservation policy).

The interventionist scenario

This scenario builds on the IPCCs B2 scenario; INRA s Le pas (walk) scenario ((Jez et al., 2007) and the Full Protection scenario developed by Henseler et al. (2009). In this scenario, economic growth has slowed, thus reducing tensions in raw materials prices (cereals and fuel). The European Union has maintained the CAP as it stood after the 2003 reform and World Trade Organization (WTO) negotiations are at a standstill. CAP subsidies have been fully decoupled except for livestock farmers. The number of dairy quotas has risen substantially. The water abstraction tax levied by the water agencies has doubled to finance major water supply programmes, so that water availability is comparable to the reference situation. Milk and meat prices are stagnant with little variability. To control leaf beetles, corn crops are limited to a statutory 40% of the usable farm area of each farm in Alsace.

For the Neste case study, water availability is assumed to have dropped by 5%, crop water needs to have risen by 5% and the standard deviation for water needs to have risen by 15%, in order to reflect increasing inter and intra-annual climatic variations (adapted from Boe et al. (2009); Caballero et al. (2007). Only in the interventionist scenario does water availability remain unchanged thanks to a programme of creation of additional water reserves. The values for the parameters chosen in each scenario are given in Table 4.1.

4.2.6 Uncertainty over the values of the main parameters

Some uncertain parameters are considered as stochastic variables. A distinction is made between Rank 1 stochastic variables and those of Rank 2, which are dependent on a Rank 1 variable. The Rank 1 random variables considered are oil prices and wheat, rapeseed and milk prices. We have assumed that these variables are independent and obey a principle of uniform distribution between two class boundaries. This decision was made because the uncertainties were such that it did not seem useful to over-represent the occurrence of certain random variables to the detriment of others by using normal or triangular distributions, as done by Gibbons et al. (2006). A random selection was therefore made between the minimum and maximum boundaries of these Rank 1 variables. Then a random selection of Rank 2 variables (which also obey a uniform distribution principle) was made according to the Rank 1 variables selected: price variations for the Rank 2 variables are proportional to price variations for the Rank 1 variables, assuming that this correlation is random. This can be illustrated by the example of oil prices (Rank 1 variable) in the interventionist scenario, where they are supposed to increase by 75% on average (deterministic value, compared

	Name of variable	Reference	Business as usual	Liberal	Interventionist
POLICIES					
	CAP subsidies decoupled from production	Partially	Fully except livestock	Fully	Fully except livestock
	Drop in Direct Payments	0%	0%	35%	0%
	Compulsory fallowing	Yes	Yes	No	Yes
	Extra irrigation premium	Yes		No	
	Energy crops on fallow land	Yes	Yes	No	
	Increase in milk quotas	0%	10%	50%	30%
	Grassland ploughing	Banned	Banned	Authorised	Banned
	Carbon premium	Yes	Yes	No	Yes
	Oil produced from rapeseed	No	Yes for livestock	Yes	Yes for livestock
	Increase in water abstraction tax	0%	0%	300%	100%
	Fuel tax exemption (0.5€/l)	No	No	Yes	non
ECONOMIC					
Rank 1	Fuel prices	0%	+100 to +200%	+200 to +300%	+50 to +100%
Rank 2	Fertiliser prices	0%		30% to 50% of fuel PV	
Rank 2	Drying costs	0%		40% to 60% of fuel PV	
Rank 1	Wheat prices	0%	10% to 30%	25% to 50%	-5% to 15%
Rank 2	Corn & cereal prices	0%		80% to 120% of wheat PV	
Rank 3	Seed corn prices	0%		25% of corn PV	
Rank 1	Rape seed prices	0%	0 to +20%	+40 to +70%	-10 to + 5%
Rank 2	Other oilseeds and pulses	0%	40 to 60% of rapeseed PV	+/-10% of rapeseed PV	80% to 120% of rapeseed PV
Rank 2	Soybean prices	0%		0 to 30% of rapeseed PV	
Rank 1	Milk prices	0%	+5% to +15%	+15% to +25%	-5 to +5%
Rank 2	Meat prices	0%	40% to 60% of milk PV		80% to 120% of milk PV
Rank 2	Animal feed prices	0%		50% of wheat PV +50% of rape price var.	
Rank 2	Prices for straw	0%		- 25% of wheat PV	
CLIMATIC					
	Increase in average water demand for crops	0%		5%	
	Increased in standard deviation for water demand	0%		10%	
	Drop in water availability	0%	5%		0%

Table 4.1: Uncertainties associated with stochastic variables for the three scenarios considered. PV: price variation

to the reference scenario), and the minimum and maximum boundaries are fixed around the +75% deterministic value to +50 and +100% respectively. Assuming that the random selection has given it a value of +85%, this will have an impact on the price of fertilizer (Rank 2 variable). Assuming then, that the correlation between these two variables is known but not with certainty, in other words that fertilizer prices vary on average by 40% of oil prices with a range of uncertainty of +/- 10%, a random selection of the degree of correlation of fertilizer prices with oil prices was carried out, for example 32%. The variation in fertilizer prices thus reached 85% x (1 + 32%), or a 12% increase in fertilizer prices compared to the reference value.

It was not chosen to associate an uncertainty with nitrate leaching estimated here with the post-harvest nitrate residue, as Gibbons et al. (2006) do with nitrogen related Green House Gas (GHG) emissions. This is because our work concentrates on uncertainty related to the economic parameters and their impact in the modeling. Gibbons et al. (2006) focus on the uncertainty related to the bio-physical mechanism of emissions. In our case, the nitrate leaching indicator stands for an average impact (i.e. over several climate years) and not for an annual or instantaneous impact, since it is used as a proxy for the pollutant load that results from the sum, over several years, of nitrate residue transport up to the groundwater.

Two hundred random selections were made for each scenario to simulate, for each type of farm, the effects of these scenarios and to analyse the distribution (minimum, maximum, average, mean and standard deviation) of the main parameters analysed (cropping patterns, water demand, marginal water cost, income, post-harvest nitrate residue). The results are described in the next two sections. The results for each study area were aggregated from the distribution of types in each zone in order to obtain results for the basin as a whole. The simulation phase involved 3600 simulations in Alsace and 6600 in the Neste basin, each simulation includes the optimisation and result processing phase.

4.3 Results at different scales on uncertainty and impact assessment

4.3.1 Impact of scenarios on water abstraction in the Neste region

Results at basin scale

The main aggregated results at basin scale and for all simulations are given in Table 4.2. At basin scale, only the liberal scenario has a significant impact on farm incomes. The water volumes used increases in all scenarios despite lower water availability. This increase is accounted for by the fact that irrigated crops can more easily compensate for a drop in income. Despite increased water consumption, the irrigated area is stable or smaller, reflecting higher irrigation intensity per hectare. On the one hand, farmers take more risk by increasing their water consumption because it increases the probability to face administrative water restrictions and, on the other hand, they try to limit the risk by concentrating reliable water supplies on a smaller area. The main reason is the removal of the irrigation premium (included in the direct payments), which they can no longer rely on as an income. Another noteworthy point is the steep decline in irrigated corn areas in all three scenarios. This trend is more significant in the liberal scenario, where farmers not only reduce the area for the reasons given above, but also replace irrigated corn with irrigated soybeans. However, these average basin-scale results mask the diversity of the results obtained and their dispersion.

	REF	BAU	Liberal	Interventionist
Income indicator (Million €)	40.1	-0.2%	-23.8%	-4.1%
Total irrigated corn area (hectares)	13 398	-14.6%	-26.5%	-7.4%
Total irrigated area (hectares)	17 324	-2.6%	+1.5%	-0.8%
Average irrigation intensity*(m^3per irr. ha)	1483	+4.2%	+6.9%	+5.8%
Total water volume used (Million m^3)	25.7	+0.3%	+0.9%	+3.7%

Table 4.2: Main average indicators for the reference situation and changes in per cent for the three future scenarios Neste case study. (*: for summer crops)

Dispersion of results at basin scale

A combined analysis of the average value of the indicators considered and their dispersion allowed to analyse the uncertainties regarding the impacts of the different scenarios.

Compared to the reference situation, the income indicator drops by 4% on average in the interventionist scenario and remains stable in the Business as Usual (BAU) scenario (see Table 4.2). An analysis of the distribution of simulation results (Figure 5.5) also shows that, in the interventionist scenario, 78% of the randomly generated scenarios result in lower margins compared to the reference situation, which is new information. Similarly, although the average margin is unchanged in the BAU scenario, there is a 56% probability that it will be smaller and a 44% that it will be higher than in the reference scenario. The results show that none of the selections made for the liberal scenario generate a gross margin equivalent to the one in the reference scenario. In general, with a low slope of the distribution function, the average value may be used and interpreted with confidence. Further analysis shows that the intervals of total gross margins in the three scenarios overlap. This means that three different simulations for each of the three scenarios can yield the same total gross margins. For instance, simulations of the three scenarios can produce situations in which the total gross margin equals 37 million €.

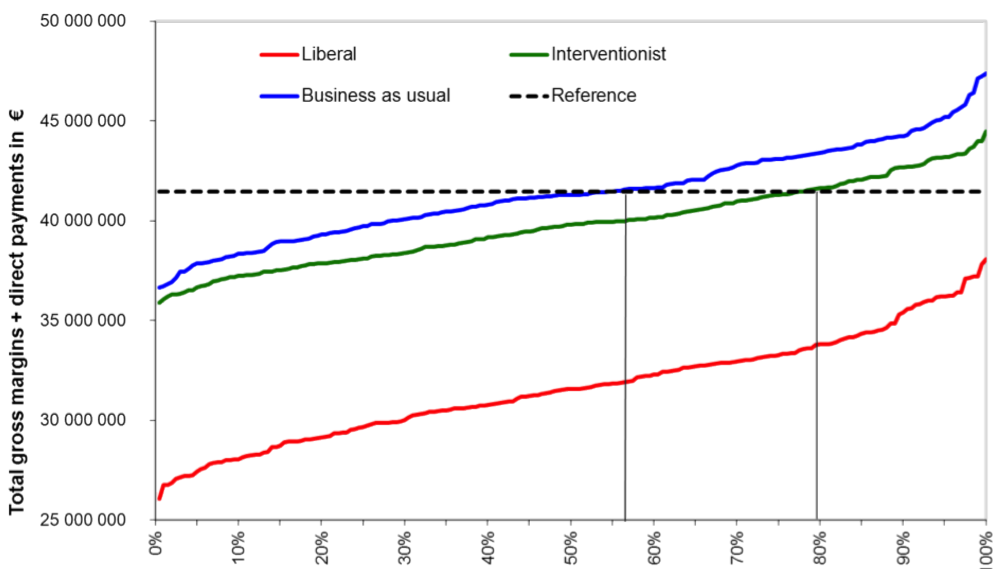


Figure 4.2: Distribution function for gross margins + direct payments in each basin-scale scenario

For some indicators or scenarios, however, the distribution function cannot be taken as a linear and continuous function. In the liberal scenario, discontinuities are observed in the water volumes consumed. Only 65% of the selections produce low slope near-linearity (cf. Figure 4.3). For the remaining 35%, there is a high probability of marked deviation from the average value.

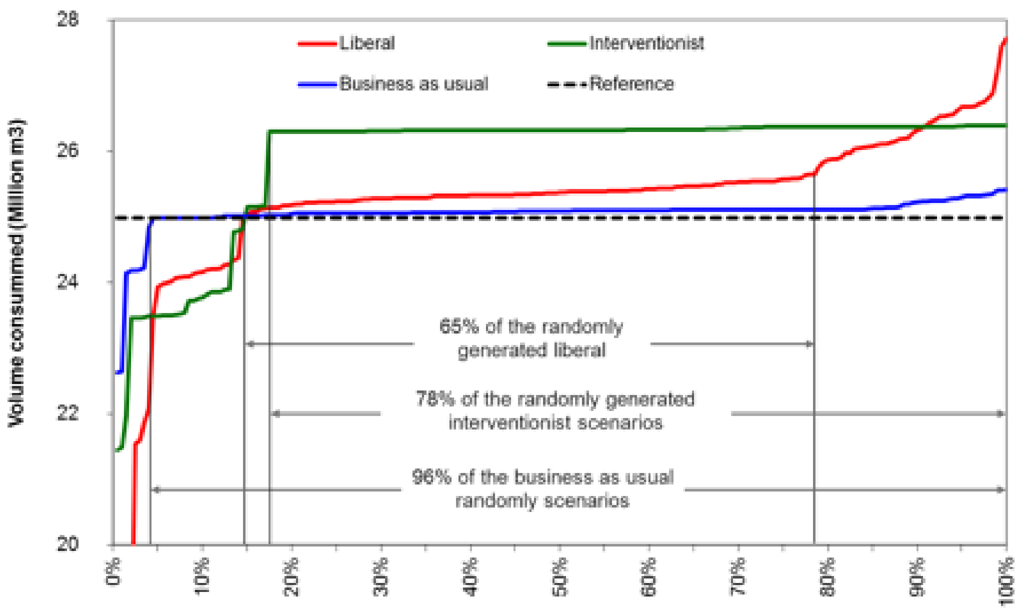


Figure 4.3: Distribution function for water volumes consumed in each scenario at basin scale

Modeling makes it possible to calculate the marginal value of water for each scenario and each farm. This may be considered as a good indicator of the risk of stress over access to water resources for different uses. The higher the marginal value of water, the more interesting the opportunities for generating economic value from each additional cubic meter of water. At basin scale, the BAU scenario produces the highest average of marginal values (0.082 €/m^3), which is roughly equivalent in the interventionist (0.055 €/m^3) and liberal (0.061 €/m^3) scenarios. As for the other indicators, the dispersion of these values must be analyzed as higher dispersion around the average reflects higher variability in the marginal value of the use of the resource. The highest dispersion of marginal values occurs in the liberal scenario (see Figure 4.4), i.e. the uncertainty is higher in the liberal scenario than in other scenarios. Furthermore, the BAU scenario is characterized by higher average marginal value of water, implying, for instance, numerous applications for water abstraction authorization or non-compliance with regulations; nevertheless the uncertainty is lower than in the liberal scenario.

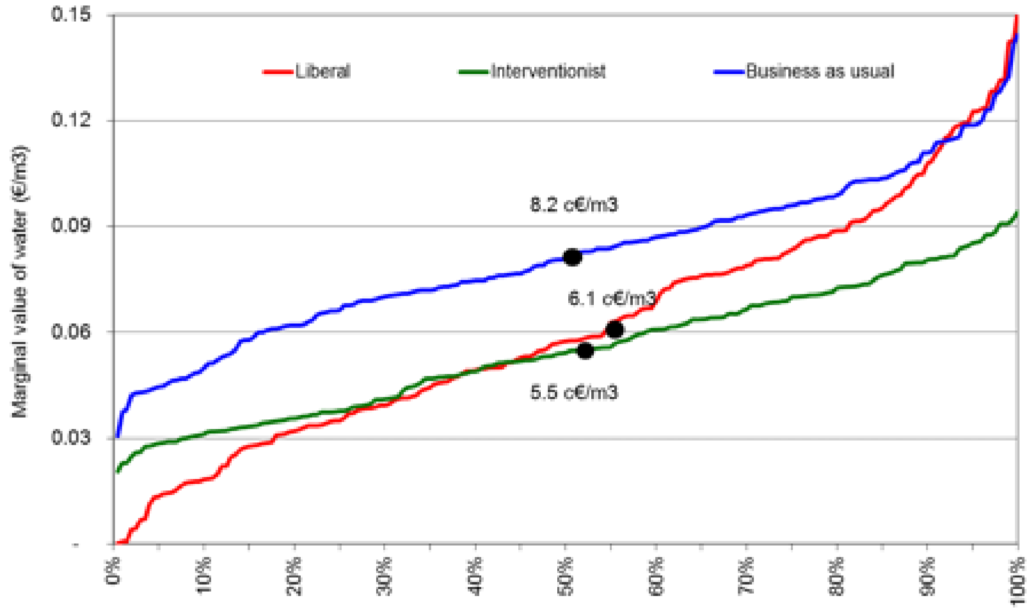


Figure 4.4: Distribution function for marginal water value at basin scale

The analysis of the main indicators at basin scale only could mask the heterogeneity between farm types or within a given farm type in any given scenario. The method and analysis developed also allow the analysis of this heterogeneity of impacts among farm types but also among farms of a same type as shown for the Alsace case study.

4.3.2 Impact of scenarios on nitrate pollution in Alsace

Results at basin scale

In Alsace, the variations in the income indicator are systematically downward compared to the reference situation, ranging from -10% to -20% (see Table 4.3).

PHNR drops by about 34% compared to the reference situation, with little difference between scenarios.

In terms of cropping patterns (see Figure 4.5), wide variations are observed compared to the reference scenario. Corn areas decline steeply in all three scenarios. The share of corn

	REF	BAU	Liberal	Interventionist
Income indicator (Million €)	337	-10%	-20%	-10%
Post harvest N residue (mean in kgN/ha)	48.4	-34%	-36%	-33%

Table 4.3: Average change with the reference scenario of the income indicator and nitrate residues modelled for the three scenarios across the entire region - Alsace case study

crops in the usable farm area drops from 62% in the reference scenario to 23%, 7% and 24% in the business as usual, liberal and interventionist scenarios, respectively. This is explained mainly by the change in the CAP subsidy system (decoupling, which no longer distinguishes the different types of crops). The biggest changes are observed in the liberal scenario: sugar beet has distinctly expanded, as quotas have been removed. Bio-energy crops have expanded significantly in all three scenarios, on the fallow or cultivated lands depending on constraints.

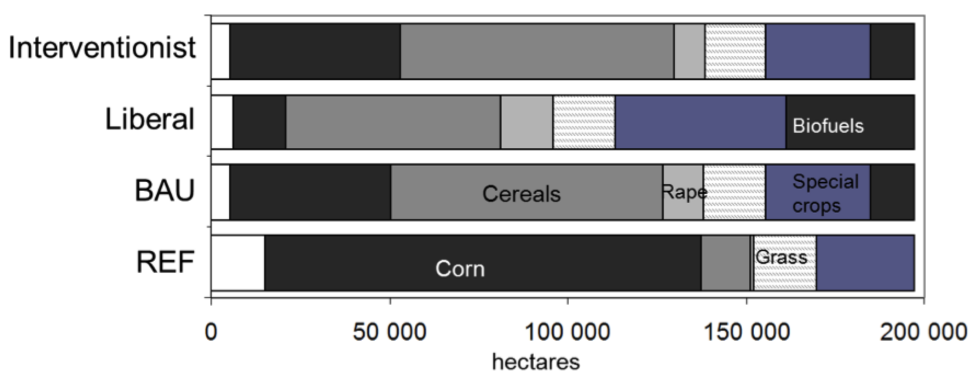


Figure 4.5: Total areas of the main crops in the three scenarios across the entire region modeled (hectares) Alsace case study

In all three scenarios, there is a significant drop of about 30% in PHNR, with marked variations. Figure 4.6 shows that residues are not evenly distributed around the average. An interpretation of these averages would suggest that the liberal scenario is less polluting than the interventionist scenario, although in some cases (i.e. for some selections) the interventionist scenario can lead to regional cropping patterns that are less polluting than the least polluting patterns in the liberal scenario (i.e. the lower boundary in the interventionist scenario is much lower than in the liberal scenario).

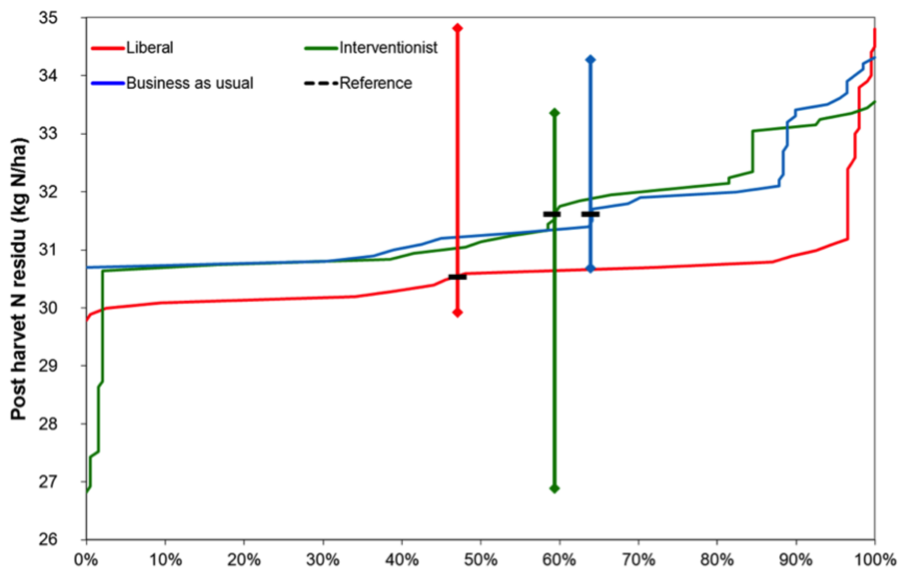


Figure 4.6: Distribution function of total nitrogen residues in each of the 3 scenarios (black dashes refer to the averages)

Heterogeneity of results between farm types

The impact of the scenarios vary from on type of farm to another (see Table 4.4): this effect appears to be lowest on corn growers (C2), where the income indicator changes by +9 to 11% compared to the reference situation, as opposed to a 28% drop in income in the small cereal-growing type (C4) and in the diversified farms (D1) types. There are also wide differences in area changes between farm types: -71% in net corn areas among the large cereal farmers in the Hardt (C1-type) against -13% only in farms where vineyards predominate, with very small corn areas. These differences also appear in the evolution of nitrate leaching: in C1-type for example, the important reduction in corn-growing areas (-71% in the liberal scenario) implies a 40% reduction in PHNR, as the crops replacing corn have a lower PHNR per hectare (wheat, sugar beet and rapeseed in particular).

Heterogeneity of the 200 simulations for one farm-type and one scenario

The 200 simulations do not systematically produce different cropping patterns, but a limited number of discrete solutions. For example, there are 14 solutions to the linear problem (i.e.

		TOTAL	C1	C2	C4	L	D1	V2
BAU	Income	-10%	-16%	-10%	-18%	2%	-19%	-10%
	PHNR	-34%	-40%	-46%	-48%	-25%	-38%	-12%
Liberal	Income	-20%	-26%	9%	-28%	-22%	-28%	-16%
	PHNR	-36%	-40%	-57%	-48%	-33%	-37%	-12%
Interventionist	Income	-10%	-18%	-11%	-20%	-5%	-18%	-6%
	PHNR	-33%	-39%	-45%	-49%	-24%	-39%	-11%

Table 4.4: Average changes of two indicators compared to the reference situation. (Income: Gross Margin + Single Payment) Alsace case study

14 cropping patterns) in the 200 simulations made for type C1 in the liberal scenario. These patterns are described in Figure 4.7, where they are referred to by a letter from A to N. Concerning nitrate residues, the values obtained for these cropping patterns are different but fairly close (29 kgN/ha within a range of -3 to +9%). The most frequent patterns (A and B) are also among the least polluting.

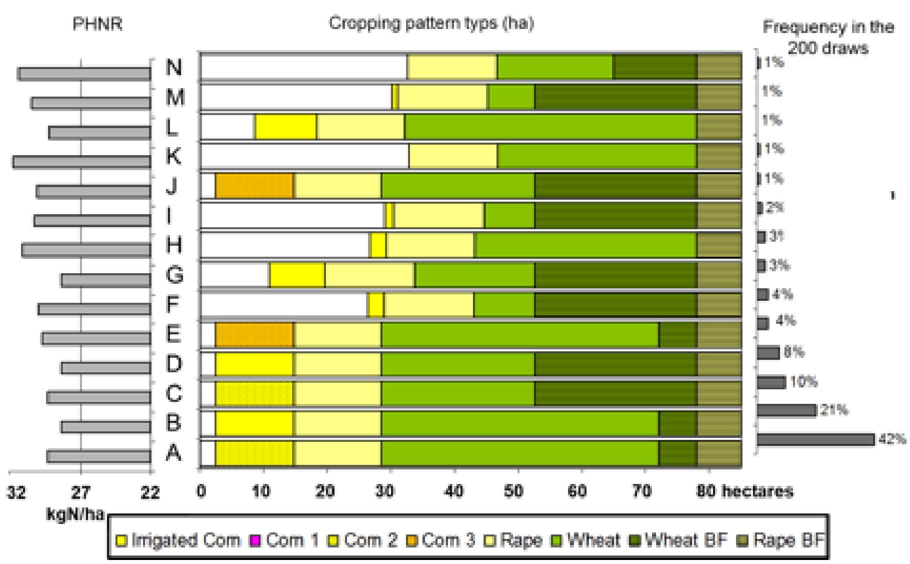


Figure 4.7: Cropping areas and their frequency in type C1 produced by the 200 simulations for the liberal scenario (in %) (white = fallow)

An analysis of the variability of nitrate residues in the liberal and interventionist scenarios for large-scale cereal farms (C1) shows a range of 28 to 32 kgN/ha in every case: the range of variation is small which is consistent with the relatively stable cropping patterns shown in Figure 4.7 (85% of the cropping pattern are the same if we consider the type of crop only, without considering neither the type of wheat nor the intensity of fertilization).

Correlation between the variability of gross margins and nitrate residues at basin scale

The variability of gross margins is of the same order of magnitude in all scenarios and ranges from -1 to -27% compared to the reference situation. Variations in nitrate residues range from -27 to -43% and are greater in the interventionist scenario. There is a tendency towards a positive variation between gross margins and nitrate residues, i.e. the more a situation tends to produce a positive result in terms of gross margins, the more polluting it is in terms of nitrate. This correlation seems logical: the greater a farmers' capacity for intensive cultivation and high nitrogen use, the more income (with corn for example). However, PHNR little varies, both with the scale of the farm (Figure 4.7) and in the zone as a whole, despite wide variations in the initial economic context. This result shows that the objective of nitrate reduction is in a small confidence interval and has thus a relative low uncertainty. In other words the policies can target a well-defined objective, which reduces the risk of policy failing.

4.4 Discussion on deterministic versus stochastic simulations

The classical approach which consists in simulating scenarios with LP or other types of models produce discrete solutions that can be named as deterministic results. This provides a deterministic picture of the outcome of the scenarios without considering any uncertainty.

The presented approach adds to this as it enables to take into account uncertainty on input parameters. It is thus interesting to compare the results produced by the Monte Carlo approach with those obtained with the deterministic approach. Table 4.5 compares the average of the Monte Carlo simulation outputs (200 simulations) for each scenario with the deterministic output. The deterministic scenarios (BAU, Liberal and Interventionist) are defined with a unique set of input parameters that correspond to the middle value of the intervals defined in Table 4.1.

The averages in all Monte Carlo scenarios differ from those in the deterministic scenarios although differences are not significant (3 to 6% differences). As a matter of fact, a deter-

	BAU		Liberal		Interventionist	
	Determ.	M-C	Determ.	M-C	Determ.	M-C
Income indicator (Million €)	311	302	288	270	311	302
PHNR (kg/ha)	34	32	34	31	33	32

Table 4.5: Income and nitrate residues in the deterministic (Determ.) and Monte Carlo (M-C) scenarios

ministic scenario illustrates a specific case which has no reason to correspond to the average situation calculated from selections made within an interval of a discontinuous function. In other words there is no symmetry of responses in the Monte Carlo simulation around the deterministic value, because of the non-continuity in the LP responses. Furthermore, the results for income and PHNR indicators are always higher in the deterministic simulations than in the Monte Carlo simulations.

The type of analysis provided by our approach is interesting for public decision making. For example, should the results of the deterministic liberal scenario be taken as a basis, the importance of potential bioenergy crops would be underestimated. Similarly, corn production and average nitrate residues per hectare would be overestimated by almost 10%. This could lead to over-investment in some sectors on the basis of overestimated supply. The identification of the most likely cropping patterns in the short-term future can help policy makers better targeting the technical and economic (incentive based) agri-environmental measures which could be promoted for water protection for instance.

The result highlights the advantage of performing Monte Carlo simulations with LP compared to deterministic simulations of LP models, which produce a discrete solution with a discrete set of input variables. As the input variables are relatively uncertain, this seems the Monte Carlo approach interesting choice to obtain reliable results.

In addition the Monte Carlo approach coupled to linear programming could be a partial response to the jumpy behaviour criticism addressed towards basic LP. The set of responses produced in all cases shows a variety of different cropping patterns which shows a more complex and less deterministic picture of what the future farming sector could be. Nevertheless, this doesn't mean that LP models coupled to Monte Carlo don't have disadvantages. Yet, the jumpy behaviour around the deterministic set of inputs can be transformed in a smoother response expressed by a density function or at least an interval. If the model itself is not better, the responses can be interpreted with more confidence as the uncertainty is reflected in the results. In other words this method provides more information to the decision makers than the deterministic method. The results of the scenario simulations are also comparable to other studies. Overall, it is found that the liberal scenario leads to significant income reduction as found in Bartolini et al. (2007). Environmental indicators also improve with the liberal scenario in both studies, even if water uptake is less affected in ours (slight reduction only). Considering the 200 selections of each scenario, incomes reductions vary from -1% to -27% compared to the reference situation in Alsace. Nitrate residues drop by -28 to -43% in Alsace compared to the reference situation, which is not a large interval, but a significant reduction. This result suggests a certain downward evolution in nitrate contamination caused by farming. Similarly, Gibbons et al. (2006) find that reducing nitrogen application is a low standard deviation adaptation to reduce greenhouse gas emission and that uncertainty on inputs doesn't matter too much, even if differences between farms can be large.

4.5 Conclusion

The methodology described has been tested in two regions to simulate the evolution of agricultural nitrate pollution (Alsace region) and the evolution of irrigation water withdrawal (Neste basin). It could be adapted to other types of environmental pressures generated by agriculture and also to more classical agricultural policy analysis. This method is suited to large areas (regional scale) but requires an important amount of data since modeling is performed on the scale of individual representative farms. This method allows assessing the impact on water resources with a confidence interval, in the zone as a whole or at smaller scales, depending on the chosen level of aggregation (farms, small farming regions or whole regions). The results support the idea that incorporating uncertainty in foresight modeling studies yields more comprehensive results to support environmental and agricultural policy planning. This is even more important when the economic context is highly fluctuating, which seems to be the case in the present period, particularly concerning agricultural market prices which are subject to strong fluctuations and uncertainty on their future evolution. The Monte Carlo simulation framework can also be useful to identify the most frequent modeled solutions i.e. cropping patterns likely to be adopted by farmers for a wide range of external economic conditions.

The approach produces interesting results: the aggregated output values simulated at basin scale for the three scenarios suggest a decline in income of around 20% in the liberal scenario and of -0.2% (Neste) and -10% (Alsace) for the BAU scenario and -4% (Neste) and -10% (Alsace) in the interventionist scenario compared to the reference situation. The environmental pressure in Alsace reduces of about -34% (+/-2% according scenarios) compared to the reference situation, with regards to nitrate residues with only small uncertainty. Concerning water use in the Neste basin, the volume abstracted should slightly increase (from +0.3 to +3.7%) whereas the evolution of irrigated area ranges between -2.6% to +1.5%, probably conducting to a general increase in irrigation intensity. The effects on nitrate leaching in Alsace are thus stronger than those on the water withdrawal in Neste. Nevertheless, values for nitrate pressure don't vary much across scenarios; this suggests that abatement policies can target a quite well-determined objective of nitrate reduction, whatever the future context. In consequence there is little risk that management plans would fail because of an error in the environmental target, in other words, that there would be an error in the decision or a policy failing due to unadapted goal. This suggests that policies won't implement too much or too little efforts and costs to reach the environmental objective.

An interesting future implementation of this joint Monte-Carlo LP method would be to explore the uncertainty relative to individual farm parameters. This should enable to explore differentiated reactions of farms to scenarios. Equity issues and before all, spatial differentiation could be enlightened. This is indeed of outmost importance when considering environmental impact of farming and environmental policy.

Appendix: Post-harvest Nitrogen Residue (PHNR) values

Activities	PHNR
wheat	37
wheat - Hardt	37
winter barley	35
corn silage (production only)	62
corn irr. 1 (low fert.) -Hardt	56
corn irr. 2 (mean fert) -Hardt	50
corn irr. 3 (high fert.) -Hardt	52
rainfed corn (high fert.) -Hardt	54
rainfed corn 1 (low fert.)	42
rainfed corn 2 (mean fert.)	49
rainfed corn 3 (high fert.)	55
rape	48
industrial rape	48
rape for raw oil	48
sugarbeet	20
sunflower	48
soy bean	52
tobacco	28
vegetables	64
wine	65
permanent grassland	17
temporary grassland	55
grass fallow	22
permanent fallow	31
IWCC	-26

Table 4.6: Post-harvest nitrogen values (PHNR). Own calculation from Schalwo data

Appendix: Annual and average corn water requirement and potential yield loss for the Neste Case study

For the Neste model, results from an agronomic model are taken to characterize yields according to water restrictions. The agronomic model calculates water needs for corn and soybeans at maximum evapotranspiration, based on climatic conditions (rainfall, potential evapotranspiration), soil characteristics (usable water reserves) and crop characteristics (see table below). Water needs at 85 %, 75 %, 65% and 50% of maximum evapotranspiration are then deduced. The model can then calculate actual yield losses compared to the target for a given irrigation application.

	Corn water requirement in m3/ha/an				
Year indice (t)	100% PET	85 % PET	75 % PET	65 % PET	50 % PET
Average	1740	1479	1305	1131	870
Potential yield loss	0%	-4.60%	-9.10%	-15.70%	-24%
1	1 390	1 182	1 043	904	695
2	1 240	1 054	930	806	620
3	1 560	1 326	1 170	1 014	780
4	2 680	2 278	2 010	1 742	1 340
5	2 250	1 913	1 688	1 463	1 125
6	1 880	1 598	1 410	1 222	940
7	2 390	2 032	1 793	1 554	1 195
8	1 780	1 513	1 335	1 157	890
9	1 420	1 207	1 065	923	710
10	2 410	2 049	1 808	1 567	1 205
11	2 040	1 734	1 530	1 326	1 020
12	1 520	1 292	1 140	988	760
13	950	808	713	618	475
14	1 800	1 530	1 350	1 170	900
15	2 250	1 913	1 688	1 463	1 125
16	2 100	1 785	1 575	1 365	1 050
17	1 230	1 046	923	800	615
18	1 030	876	773	670	515
19	1 810	1 539	1 358	1 177	905
20	1 150	978	863	748	575
21	1 290	1 097	968	839	645
22	1 340	1 139	1 005	871	670
23	1 460	1 241	1 095	949	730
24	2 780	2 363	2 085	1 807	1 390

Table 4.7: Annual and average corn water requirement and potential yield loss. Neste Case study. PET: Potential evapo-transpiration

Appendix: details to the Neste models

Neste farm types Among the whole Neste region, two sub-regions representing 25% of the number of irrigating farms and 33% of the irrigated area are considered in this application case. Eleven types of farms were considered for modeling. The typology process is based on criteria on the technical orientation of the farms (cereal, cereal and milk cows and general culture and meet cows), the usable farm area (from 20 to 75 hectares and more than 75 hectares), the percentage of usable farm area that is irrigated (less than 40% and more than 40%) and the percentage of fodder crops (0%, less than 30% and more than 30%). Among these sub-regions, the results of the crossing process lead to neglect some farm types, so that 50% of the irrigating farms and 68% of the irrigated area are represented.

Calibration of models and performance of the model Each farm type model is well calibrated since the technical constraints enable to replicate correctly the observed farm level cropping patterns. In the Neste models for instance, the irrigated area is the same as the observed area excepted for 3 types where the difference is lower than 5%. For the whole 11 types, the area of irrigated corn is 1.2% overestimated (215 ha) compared to observed area and is compensate by rain fed corn underestimation. The estimated wheat area is 2.1% underestimated (361 ha) and is compensated by the overestimation of soybeans and pulses. For the cattle breading, results reveals a good calibration of animals feed ration, fodder crops and grassland yields. Finally, results reveal a nearly full utilisation of the permanent manpower introduced in the models.

Chapter 5

Intensive and extensive margin adjustments to water scarcity in France's cereal belt

[1]

[1]This working paper has been co-authored with Pierre Mérel. We thank Sébastien Loubier for comments on an earlier working paper as well as three anonymous referees. We also thank the participants of the SFER conference (Toulouse décembre 2013) and EcoProd seminar (Montpellier septembre 2013) for interesting remarks

5.1 Introduction

Water regulations are an institutional response to these drivers. In the European Union, the Water Framework Directive (WFD) requires Member States to reach a so-called "good ecological status" of all water bodies by 2027. This terminology covers both quantitative and qualitative criteria. The means to reach such good ecological status are left to the appreciation of Member States, who are encouraged to use cost-effectiveness criteria in selecting an appropriate set of measures (European Commission, 2003), an example is provided by Berbel et al. (2011). This latter requirement necessitates assessment tools to evaluate alternative policies aimed at regulating water use and water management.

Farming typically represents one of the main pressures on water resources, through massive water withdrawal of surface and groundwater (Schoengold et al., 2006; OECD, 2010) as well as water contamination caused by the leaching of nitrates and pesticides towards water bodies. An important avenue for managing water scarcity is the reduction of the water intensity of agriculture, broadly defined as the volume of water per hectare of farmland at a regional scale.[2]

Such reduction can be achieved through three main margins of adjustments: the shift from irrigated towards rain-fed agriculture, which we call the super-extensive margin; the shift from relatively water-intensive crops, say corn, towards relatively water-saving crops, say wheat—the extensive margin; and the decrease in the irrigation rate of individual irrigated crops, or the intensive margin, also known as deficit irrigation.[3] There is a need to better understand the relative contributions of these adjustment margins to water scarcity adaptation in multi-activity cropping systems (Moore et al., 1994; Hornbeck and Keskin, 2011; Hendricks and Peterson, 2012). Ignoring any one relevant margin can lead to overestimation of the economic impact of reduced resource availability and bias cost-effectiveness measures of available policy options, potentially leading to poor decision-making (Frisvold and Konyar, 2012).

[2] Another important avenue is improvements in irrigation efficiency to increase water productivity (Gleick, 2003) through reductions in water losses due to leaching, runoff and evaporation.

[3] Short-run and long-run adaptations of farmers to water scarcity must be distinguished, as suggested by Reynaud (2009). Here we focus on long-run adaptations that occur before cropping patterns are determined at the beginning of the cropping year. The intensive margin adjustment can thus be considered as a planned deficit irrigation, as opposed to a short-run adaptation to day-to-day climatic conditions as analysed for instance by Moore et al. (1994).

The behavioural response of farmers to water scarcity or, equivalently, to water price, can be inferred using various approaches including econometrics, programming models and field experiments (Scheierling et al., 2006).[4] Field experiments typically do not allow for broad regional coverage due to their high implementation cost, and thus may lack external validity. The econometric approach typically relies on panel data on water allocation to cropping activities and irrigation costs. As argued by Hendricks and Peterson (2012), cross-sectional variation alone cannot convincingly address water demand elasticity as pumping costs may be correlated with unobservables that affect water demand. Purely time-series variation in irrigation costs is also problematic as energy prices tend to be correlated with crop and input prices. Irrigation costs may be observed directly as when water is delivered by a utility, as in Schoengold et al. (2006); identification then relies on sufficient time-series price variation, due for instance to changes in the water fee. When a water price is not directly observed and water is pumped directly by farmers, the irrigation cost may be imputed based on groundwater depth and available energy prices (Hendricks and Peterson, 2012). This last approach has the advantage of providing a source of cross-sectional and time-series variation in water price, to the extent that water depth varies across space and possibly time and energy prices vary across time. It thus allows for the inclusion of location and time fixed effects. Econometric approaches are generally data intensive; for instance Schoengold et al. (2006) use an 8-year panel of 117 land blocks, while Hendricks and Peterson (2012) use a 16-year panel of 14,000 individual fields. As a result, programming methods still dominate the literature on estimating the water demand elasticity, as is confirmed by the meta-analysis of Scheierling et al. (2006).

Accordingly, the present paper proposes a calibrated programming approach to investigate the behavioural response of farmers to regional water scarcity in the empirically relevant context of France's main cereal region.

Programming models (PM) of agricultural supply have been used extensively in the literature to simulate the impact of water scarcity, water quality and water policies on agriculture (Dinar et al., 1991; Ribaudo et al., 1994; Weinberg and Kling, 1996; Posnikoff and Knapp, 1996; Schwabe et al., 2006; Maneta et al., 2009; Medellín-Azuara et al., 2010; Graveline et al., 2012). PM models typically describe the allocation of inputs among activities as the result of the maximisation of profit, subject to resource and policy constraints. Some authors also adopt different objective functions that account for risk (i.e. expected profits)

[4] The Data Envelopment Analysis method has also been applied to this issue (Speelman et al., 2009; Frija et al., 2011).

or for other attributes than profit (Gòmez-Limón and Riesgo, 2004; Bartolini et al., 2007; Latinopoulos, 2008). While some models specify a fixed-proportion relationship among productive factors (Ribaudo et al., 1994; Bartolini et al., 2007; Clark and Peterson, 2008; Balali et al., 2011; Graveline et al., 2013), PM can accommodate detailed production functions with several productive factors while allowing for input substitution, and therefore intensive margin adjustments.

PM that allow for such adjustments can be characterised as belonging to two broad strands of literature. The first strand, by far the most prolific, has focussed on capturing biophysical processes affecting crop yields in the context of a linear programming representation of crop choice. Some studies are fully cast within linear programming and capture the dependence of yield on input intensities through the specification of multiple cropping activities with varying levels of input use (McCarl and Schneider, 2001; Cortignani and Severini, 2009; Graveline et al., 2012). Other models explicitly assume that yields depend non-linearly on input quality or quantity, but, conditional on inputs, that they are constant across acreage planted (Dinar et al., 1991; Weinberg and Kling, 1996; Posnikoff and Knapp, 1996; Connor et al., 2009; Durandeau et al., 2010).

The second strand of literature encompasses positive mathematical programming (PMP) models of regional supply that allow for input substitution (Howitt, 1995a; Medellín-Azuara et al., 2010; Mérel et al., 2011; Frisvold and Konyar, 2012). These models assume, implicitly or explicitly, that yields are decreasing in acreage planted due for instance to land heterogeneity or rotational effects.[5] However, their implied yield responses to input intensities are typically not calibrated to any sort of biophysical information, and thus remain largely uncontrolled for.

The present study contributes to bridging the two strands of literature, in the sense that our inference relies on a PMP model of input allocation at the regional scale that exactly calibrates to exogenous agronomic yield responses to irrigation intensity.

Our empirical setting is France's Beauce region. Beauce is the main cereal supplier in Europe (Eurostat, 2012). Since the seventies, irrigation has developed substantially to cope with dry years, secure high yields and permit diversification of crop production. Irrigation essentially relies on a large groundwater resource, the Beauce aquifer, which faces quantitative problems, as evidenced by the lowering of the water table since the beginning of

[5] PMP models with increasing marginal costs and constant yields have been justified heuristically by decreasing marginal land quality. As such, they implicitly assume that yields would decrease with acreage were it not for the increased expenses incurred to keep yields constant.

the nineties and droughts on dependent surface rivers. Water use in the Beauce region is subject to the French Water Law of 1992 and, since 2000, the European WFD (European Commission, 2000). A policy of reduction of maximum allowable water withdrawals for agriculture has been in place since the late nineties to limit groundwater depletion (Petit, 2009). In this context, there is a clear need to understand how farming can adapt to water scarcity and to assess the costs of reduced water availability to agriculture. Alternative policies also need to be envisioned to allow further adaptation at the regional scale and reduce the social costs of water scarcity. To that effect, we simulate the impacts of various water scarcity scenarios on economic profit, cropping patterns and irrigation practices and assess the relative contributions of the various adjustment margins to overall adaptation. We also investigate the possibility of water quota transfers across sub-regions as a way to mitigate reduced water scarcity.

Our model is based on the principles of PMP (Howitt, 1995b), which uses a non-linear objective function in order to replicate an observed input-output allocation. We specify crop-level production functions that explicitly allow for substitution between land and water and calibrate them to replicate a set of exogenous agronomic crop yield responses to water intensity. This additional calibration, the principles of which have been discussed recently by Mérel et al. (2013), is critical to accurately represent intensive margin adjustments and associated yield effects at the regional scale. It further addresses the critics of Koundouri (2004a), who argues that programming models concerned with groundwater management ignore the intensive margin adjustment and use functions that may not represent biological processes.

The non-linearity in our PMP objective arises from decreasing returns to scale at the crop level, rather than increasing marginal costs as often assumed in existing PMP models (Cortignani and Severini, 2009; Frisvold and Konyar, 2012; Medellin-Azuara et al., 2012). To investigate the robustness of our inference to the available economic information used for calibration, the returns-to-scale parameters are calibrated using two alternative information sources. First, following recent trends in the PMP literature (Mérel and Bucaram, 2010; Mérel et al., 2011), we use exogenous supply elasticities. Such a calibration rule ensures realistic responses to price changes. Second, because we are interested in evaluating the impact of water reduction on agricultural profits, we use a calibration rule whereby the objective function exactly coincides with observed accounting profit in the reference allocation. We also implement a hybrid approach. Overall, our results are consistent across models. Notably, we find that the intensive margin adjustment represents a non-negligible share of the total water reduction at the regional scale, even with conservative estimates of the substitution elasticity. The bulk of the response (about 80%) comes from extensive and super-extensive margin adjustments. Significant differences are observed across spring and summer crops, providing relevant information for intra-annual water management.

Overall, this work illustrates the usefulness of our calibrated approach towards addressing quantitative water policy questions at the level of an entire groundwater basin in an agriculturally significant region.

The article is organised as follows. Section 5.2 explains the institutional background of water management in the Beauce region. In section 5.3 we describe the programming model representing the allocation of land and water resources among activities at the regional level. Section 5.4 presents the data used to calibrate the model. In section 5.5 we present the results of a simulation of reduced regional water availability. Section 5.6 concludes.

5.2 Background

The Beauce region (9,700 km2), located in the centre of France, is its most productive cereal region (Eurostat, 2012). Beauce sits on two administrative regions ("Centre" and "Ile de France") and six administrative departments, covering about 650,000 hectares of farmland. The Beauce aquifer, once called the "château d'eau" (water tower) of France, is used for irrigation, drinking water and industry. It also feeds natural surface water systems, including the Loire river, thereby providing important ecosystems services (wetlands, biodiversity). The Beauce region is host to intensive cereal- and oilseed-oriented agriculture, wheat being the major crop (34.5% of sweet wheat and 13.2% of durum wheat), followed by barley (21.1%) and rapeseed (11.2%), as well as corn (7.6%), sugar beet, potatoes, and vegetables. The administrative "Centre" region is the first European region for wheat and rapeseed production (Eurostat, 2012). Figure 6.1 shows a map of the area.

Starting in the early sixties, irrigation in Beauce developed steadily for about thirty years to secure yields in dry years, with sharp accelerations in adoption after severe drought events, notably in 1976. Currently, depending on the year between 120,000 and 240,000 hectares are irrigated with pivots and hose reels irrigation systems, withdrawing between 150 and 450 millions of cubic meters per year. This technology is arguably the best suited for field crop irrigation in this area. Access to groundwater is individual through wells. Two irrigation periods can be distinguished: (i) spring irrigation (wheat and barley mainly) and

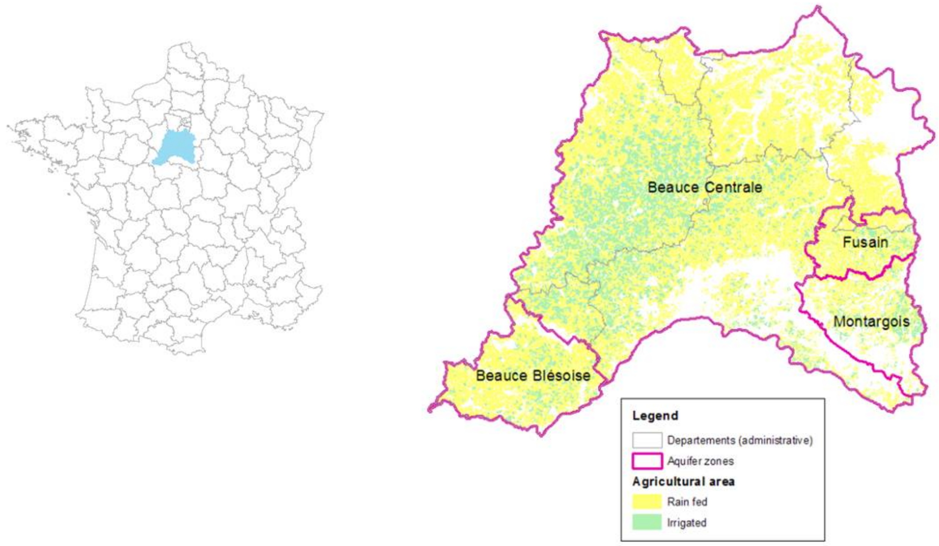


Figure 5.1: Situation map of the Beauce aquifer and agricultural areas

(ii) summer irrigation (corn, sugar beet, potatoes, and vegetables). Corn is irrigated on 85% of the total corn acreage, while barley and durum wheat are irrigated on a quarter of their respective acreage. Sweet wheat is only irrigated on 13% of its acreage. In the early nineties, concerns about the sustainability of water withdrawal from the aquifer to cope with drought events has fostered the implementation of water use regulations. The European WFD further requires that a good quantitative state of the Beauce aquifer be ensured.[6]

Historically, the first strategy of the government was to impose pumping restrictions on some summer days. Later on, a more formal system was introduced, consisting of a three-tier alert system based on the piezometric level of the aquifer. Once a threshold was reached, additional pumping restrictions were implemented. Since 1999, the system has changed and is based on individual quotas. Each year, a coefficient reflecting the state of the groundwater at the beginning of the cropping season is established by the government. This coefficient is multiplied by the quota to determine the volume that can be pumped each year. There are no restrictions on the dynamic use of water, which means it can be used partially or totally on spring or summer crops. Therefore, farmers have to plan both cropping and irrigation patterns jointly, at the beginning of the campaign, under uncertainty on climate

[6]The Beauce aquifer also encounters quality problems arising from high nitrates and pesticides concentrations in groundwater.

parameters. An option to transfer unused water rights from one year to the next was tested, but it was abandoned because of high transaction costs and poor relevance with hydrogeological dynamics, notably inertia of the aquifer.

Since 2008, in order to better reflect hydrogeological characteristics of the aquifer, the pumping coefficients have been differentiated across four sub-areas, each corresponding to a distinct hydrogeological zone (Petit, 2009). The zoning corresponds to differences in the following hydrogeological properties: infiltration time, reaction to climate, and thickness of aquifer. The current policy could be characterised as a "central control" policy (Provencher and Burt, 1994) with differentiation of withdrawal capacity per zone, but without accounting for the seasonality of withdrawals or the option to trade water rights.

The Beauce water policy problem is not an isolated case. In southern Europe and worldwide, large agricultural systems often rely on scarce groundwater resources that are subject to increased demands as well as limited recharge due to the effects of climatic change, for instance, the La Mancha aquifer in Spain or the Ogallala aquifer in the United States.

5.3 Model

In order to analyse the implications of water scarcity and mitigation policies on the agricultural sector in Beauce, we calibrate a regionalised PMP model with crop-specific production functions under land and water constraints.

Our model displays decreasing marginal yields at the crop level and constant elasticity of substitution (CES) between land and water for irrigated activities. We exploit publicly available agronomic information to calibrate the yield response elasticities to water of irrigated crops, as suggested recently by Mérel et al. (2013). This calibration ensures a realistic yield response to water reductions in the vicinity of the initial equilibrium. Our model assumes that inputs other than irrigation water are used in fixed proportions with land.[7]

Even when calibrating yield responses to input intensities, there remains several ways to calibrate the programming model to ensure the replication of an observed input-output allocation. To remedy this under-determinacy, the recent literature has advocated the use

[7] An alternative model could consider fertilizer inputs as a separate input substitutable to land and water, as in Mérel et al. (2013). Medellin-Azuara et al. (2012) also integrate capital investment for irrigation technology as an input that can substitute applied water in a nested CES function.

of supply elasticities (Heckelei and Wolff, 2003; Mérel and Bucaram, 2010; Mérel et al., 2011), and one variant of our model relies on such information.

Alternative calibration rules exist, such as the calibration of average costs so that the objective function in the reference situation replicates observed crop-level accounting profits. Such a rule has been referred to as the "average cost approach" in the context of positive quadratic programming (Heckelei, 2002). We implement it as a second variant to our model, as we are interested in the impacts of increased water scarcity on the profitability of agriculture in the Beauce region.

We also implement a hybrid calibration rule that makes use of both supply elasticities and baseline accounting profits, using generalised maximum entropy (GME). This calibration rule allows us to calibrate the shadow value of water in the reference allocation without implementing the first stage of PMP—thereby avoiding a critique by Heckelei and Wolff (2003). We systematically compare the three approaches when presenting our results.

5.3.1 Regional modeling

Our choice to represent cropping decisions at the regional scale, rather than at the individual farm type level, is driven by three main reasons. First, it enables us to use good quality, high confidence data systematically produced at the administrative department level by the ministry of agriculture, notably on crop yields. Second, it allows to represent a very large share (90%) of the cultivated area, which would have been difficult with a typology of farms. Finally, it makes the best possible use of the information we have on crop yield responses to water, which is available by broad soil type, but not by farm type. This is essential as our purpose is to accurately represent intensive and extensive margin adjustments to water scarcity.[8]

Our choice of a regional scale is not without its shortcomings. First, it does not allow us to analyse equity issues across farm types. However, there is only limited heterogeneity across farm types in the region as shown by Hérivaux (2013) who states that 94% of the usable farm area over the Beauce aquifer is grown by the *Field crops* FADN farm type (based on 2010 census data). Second, the assumption underlying our regionalised approach to agricultural

[8]Godard et al. (2008) are able to integrate agronomic information on yield responses to nitrogen in the context of a farm-level linear programming model. They generate a large series of potential yield response curves conditional on climate, soil type and cultural practices. They circumvent the lack of information on a farm's actual characteristics by selecting the yield response curve that fits the economic information (yield level and price ratio of fertilizer over output price) best. This approach implies that a large amount of agronomic information is discarded.

supply is that scarce resources (land and water) are transferable within each region, and individual production units are price-takers with respect to land and water. While we can safely argue that there is a market for land[9] and that production units are small enough to be considered atomistic, the fact that water quotas are tied to the land could be seen as problematic. We do not believe this is likely to cause big aggregation problems. Imagine for instance two farms A and B, with the marginal productivity of water much higher on farm A than on farm B. Then, even in the absence of a formal market for water, there would exist an economic incentive for farmers A and B to consolidate their resources and allocate the aggregate water rights optimally on the new land A+B. Therefore, to the extent that a land market exists, our regionalised model should replicate a decentralised allocation without suffering too much from aggregation bias. One way to mitigate such aggregation bias is to reduce the size of the regions (as suggested by Garay et al. (2010)). We do this by considering four sub-regions corresponding to the four hydrogeological zones subject to the differentiated irrigation constraints.

5.3.2 Model structure

The regional optimisation model is specified as follows:

$$\max_{\substack{\mathbf{x}\geq 0\\ \mathbf{q}\geq 0}} \sum_{i=1}^{I} \{p_i q_i - (c_{i1}+\mu_{i1})x_{i1} - (c_{i2}+\mu_{i2})x_{i2}\}$$

$$\text{subj. to} \quad \begin{cases} \sum_i x_{i1} \leq b_1 & [\lambda_1] \\ \sum_i x_{i2} \leq b_2 & [\lambda_2] \\ q_i = \alpha_i \left(\beta_{i1} x_{i1}^{\rho_i} + \beta_{i2} x_{i1}^{\rho_i}\right)^{\frac{\delta_i}{\rho_i}} \end{cases} \tag{5.1}$$

where the regional indices are omitted for clarity. In program (5.1), p_i denotes the price of the output of activity i and q_i is the output, related to regional inputs through a CES production function with parameters $\delta_i \in (0,1)$, $\rho_i \in (-\infty,0)\cup(0,1)$, $\alpha_i > 0$, and $(\beta_{i1},\beta_{i2}) \in [0,1]^2$ normalised such that $\beta_{i1}+\beta_{i2}=1$. The inputs explicitly considered are land (x_{i1}) and water (x_{i2}). We set $\beta_{i2}=0$ for rain-fed activities. The land input includes all other inputs necessary for agricultural production (fertilizers, pesticides, etc.), which are assumed

[9]The land control policy implemented through the creation of the SAFERs, *Sociétés d'aménagement foncier et d'établissement rural* in the sixties and their pre-emptive right to buy agricultural land has a modest effect on the market. Indeed they only bought 16% of the areas in the market and sold only 5% in 2011 (Source: www.safer.fr accessed on 29 april 2013). Coulomb (1999) also shows that even though the SAFERs can intervene in the market, land prices follow supply and demand.

to be employed in fixed proportions with land. The elasticity of substitution between land and water is $\sigma_i = \frac{1}{1-\rho_i}$. The regional land and water availabilities are denoted b_1 and b_2. The observed per hectare costs of activity i are c_{i1}, while the observed cost of water is c_{i2}. This cost includes pumping costs as well as fees charged by the water basin authority. To these observed costs, we add the PMP shadow costs μ_{i1} and μ_{i2}, which are behavioural parameters used to rationalise the observed input-output allocation under the assumption of profit maximisation. The shadow land costs μ_{i1} are used to replicate the observed cropping pattern in the reference allocation. The shadow costs μ_{i2} are used to rationalise the observed irrigation rate, given the regional yield responses to water application.

The observed reference allocation consists of a set of crop-level acreages $\bar{x}_{i1}$, irrigations $\bar{x}_{i2}$, outputs $\bar{q}_i$ as well as shadow prices of constrained resources $\bar{\lambda}_1$ and $\bar{\lambda}_2$. The shadow prices can be obtained from the first stage of PMP (Howitt, 1995b), or, alternatively, may be inferred from observed rents (Gohin and Chantreuil, 1999). In this application, we use a hybrid approach where the shadow price of land $\bar{\lambda}_1$ in each region is inferred from observed agricultural land prices, while the shadow price of water is obtained from the first stage of PMP in the first two calibration approaches. In the hybrid calibration approach, the shadow value of water is recovered endogenously.

The first-order conditions to program (5.1) imply that conditional on the choices of δ_i and ρ_i, information on the reference input-output allocation and the yield responsiveness to water allows one to recover the technology and behavioural parameters $\boldsymbol{\theta}_i = (\alpha_i, \beta_{i1}, \beta_{i2}, \mu_{i1}, \mu_{i2})$. Calibration of the model is done recursively. First, the substitution parameters ρ_i are set using exogenous values for the land-water substitution elasticities. The returns-to-scale parameters δ_i can then be calibrated independently of the technology parameters $\boldsymbol{\theta}_i$ using exogenous information on crop supply elasticities (Mérel et al., 2013) or, as we show below, by specifying that reference profits should be replicated by the calibrated model. Conditional on the values of the parameters ρ_i and δ_i, the parameters in $\boldsymbol{\theta}_i$ are then calibrated to replicate yield response elasticities and the reference input-output allocation.

5.3.3 Calibration against observed supply elasticities

The first approach we use to calibrate the technology parameters of program (5.1) is the supply elasticity calibration first described by Mérel et al. (2011) and, in the context of a model with calibrated crop yield responses to inputs, by Mérel et al. (2013). The main advantage is the replication by the model of exogenous own-price supply elasticities, and thus its ability to avoid erratic responses such as those typically observed in linear programming models (Gohin and Chantreuil, 1999). One disadvantage underscored by Mérel et al. (2011) is the existence of calibration conditions that might exclude certain sets of elasticities. When this happens, the set of exogenous supply elasticities needs to be reconsidered so as to allow for calibration, but this can be done at a minimum information cost through the use of generalised maximum entropy (Golan et al., 1996). Once a reproducible set of elasticities is found, calibration of the δ_i parameters involves solving a non-linear system of equations relating the model's implied supply elasticities to the exogenous priors. The structure of this calibration system is borrowed from Garnache (2010) and is given in Appendix A.

5.3.4 Calibration against observed profits

In contrast to the calibration against exogenous supply elasticities, the second calibration approach we use does not necessitate information beyond that included in the reference input-output allocation to calibrate the returns-to-scale parameters δ_i. The idea behind this approach is that the calibrated non-linear objective function should be equal to the first-stage linear program objective under the reference conditions. This criterion allows one to directly interpret the value function of the non-linear program as reflecting aggregate farm profits, an interpretation arguably more subject to caution when using alternative calibration rules. In our model, farm profits include returns to the ownership of scarce factors (here land and water) as well as Ricardian rents arising from the concavity of the crop-level production functions. Heuristically, these rents may reflect returns to input heterogeneity and managerial ability. Replication of regional farm profits represents an advantage when the purpose of the policy model is to predict the effect of policies or shocks to farm income. The drawback of this approach is that the output responses to own-price changes are no longer controlled for.

Crop revenues ($p_i\bar{q}_i$) are typically calibrated since the model replicates not only crop acreage but also crop yields. Therefore, calibrating crop-level profits implies that total PMP costs, $\sum_{l=1}^{2}(c_{il}+\mu_{il})\bar{x}_{il}$, must be equal to the observed accounting costs in the reference allocation, $\sum_{l=1}^{2} c_{il}\bar{x}_{il}$. The determination of δ_i is then straightforward from the first-order conditions of the model:

$$\delta_i = \frac{(c_{i1}+\bar{\lambda}_1)\bar{x}_{i1}+(c_{i2}+\bar{\lambda}_2)\bar{x}_{i2}}{p_i\bar{q}_i}. \tag{5.2}$$

Since we use exogenous information on land rents to determine $\bar{\lambda}_1$, and these land rents are lower than those inferred from the first stage of PMP, all activities will display decreasing returns to scale, that is, $\delta_i < 1$ for all i.

Figure 5.2 presents a schematic interpretation of the elasticity and cost calibration rules for a typical crop i in the simple case where there is no input substitution ($\sigma_i = 0$ and $q_i = \alpha_i x_i^{\delta_i}$). We introduce total per hectare costs $C_i = c_{i1} + \frac{\bar{x}_{i2}}{\bar{x}_{i1}} c_{i2}$ and similarly $\bar{\lambda}_i = \bar{\lambda}_1 + \frac{\bar{x}_{i2}}{\bar{x}_{i1}} \bar{\lambda}_2$. The top panel represents the cost calibration approach, where no PMP cost is added in order to replicate observed costs and observed profit at the crop level. The two parameters of the production function, α_i and δ_i, are chosen so that at the observed acreage $\bar{x}_i$, (i) the marginal revenue $p_i \alpha_i \delta_i x_i^{\delta_i - 1}$ equals the per acre costs $C_i + \bar{\lambda}_i$ and (ii) the crop revenue, corresponding to the lightly shaded area, equals the observed crop revenue $p_i \bar{q}_i$.

The bottom panel illustrates the elasticity calibration. The set of potential marginal revenue curves that would replicate observed revenue is depicted with thin dotted curves. All these curves satisfy the property that the area beneath them up to the acreage $\bar{x}_i$ is equal to $p_i \bar{q}_i$. Among these potential marginal revenue curves, the elasticity calibration procedure selects the one with the particular slope at $\bar{x}_i$ that replicates the desired crop supply elasticity, depicted as the thick dotted line. Once this marginal revenue curve has been selected, the shadow cost μ_i is added to the per hectare costs so that at the observed prices, marginal revenue equals marginal cost at exactly $\bar{x}_i$.

5.3.5 Hybrid calibration

We further implement a calibration rule that exploits the two previous sources of information, namely supply elasticities and baseline crop profits, to jointly calibrate the model parameters δ_i and μ_{i1}, while still allowing for the replication of the reference allocation and exogenous yield elasticities to irrigation. Because the model is now over-identified, we solve the calibration problem within the framework of GME (Golan et al., 1996; Heckelei and Wolff, 2003). The over-identification of the model further allows us to avoid using the first stage of PMP to recover the shadow value of water. Instead, the shadow value of water is solved as part of the GME program. As before, the shadow value of land is based on observed regional land values.

We specify support intervals for the model supply elasticities that are centered on the exogenous values used in the elasticity calibration rule, allowing for a 70% deviation from the central value. To keep crop profits within a reasonable range of the baseline, we specify

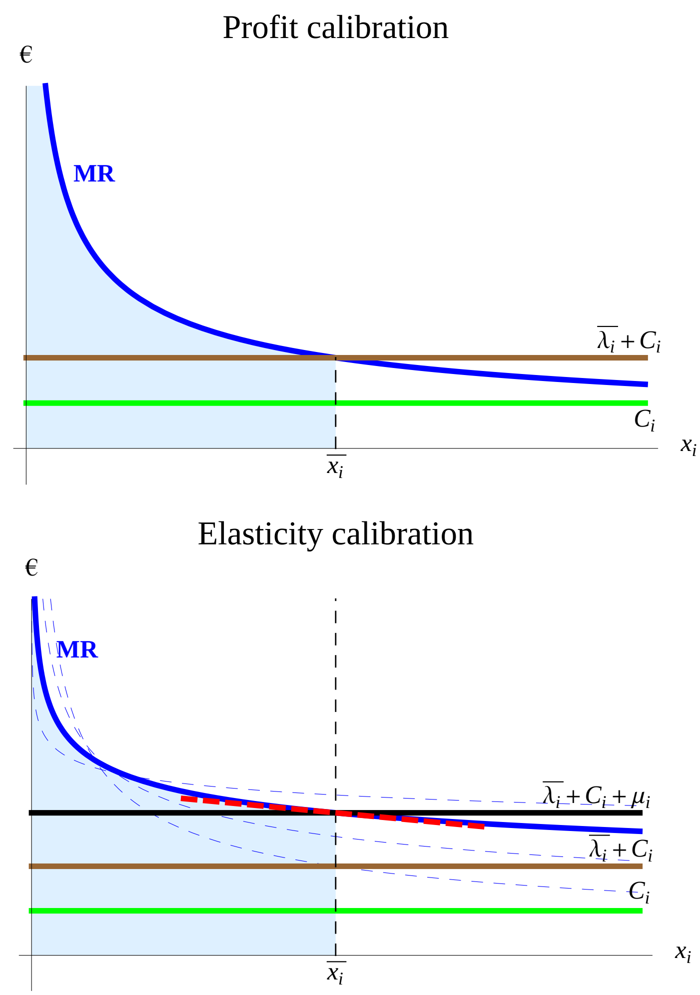


Figure 5.2: Schematic illustration of the two calibration approaches

that the sum of the total shadow costs, $\mu_{i1}\bar{x}_{i1} + \bar{x}_{i2}\mu_{i2}$, lies within 35% of baseline profits. Parameters are chosen such that the calibrated model exactly replicates baseline acreage and outputs, as well as water-yield elasticities. The formal structure of the GME program is given in Appendix B.

5.3.6 Calibration of the agronomic yield response

In addition to reproducing the reference input-output allocation and supply elasticities or crop profits, the crop-level profit functions in the CES model can be calibrated so as to replicate the agronomic response of yield to water at the reference point (Mérel et al., 2013). Agronomic data on crop yields as a function of irrigation intensity is needed (field experiments, regional statistics or expert knowledge) to fit yield response functions to water for irrigated crops. The functional form we use to represent the yield response function to water is:

$$y_i(w_i) = \frac{a_i}{1 + \exp\left(-\frac{w_i - w_{i0}}{b_i}\right)}$$

where the unknown parameters are a_i, b_i and w_{i0}, w_i denotes water intensity and y_i is yield. This functional form is flexible enough to allow for a sigmoidal response to water with a horizontal asymptote for large irrigation values. The unknown parameters a_i, b_i and w_{i0} are estimated using non-linear least squares (NLS). The implied yield response elasticity at the observed irrigation level $\bar{w}_i = \frac{\bar{x}_{i2}}{\bar{x}_{i1}}$ is then:

$$\bar{y}_{iw} = \frac{\bar{w}_i \exp\left(-\frac{\bar{w}_i - \hat{w}_{i0}}{\hat{b}_i}\right)}{\hat{b}_i \left(1 + \exp\left(-\frac{\bar{w}_i - \hat{w}_{i0}}{\hat{b}_i}\right)\right)} \tag{5.3}$$

where the NLS estimates are indicated with hats.

The yield elasticities with respect to water from the CES model are set equal to the agronomic yield elasticities:

$$\bar{y}_{iw} = \delta_i \frac{\beta_{i2}\bar{x}_{i2}^{\rho_i}}{\beta_{i1}\bar{x}_{i1}^{\rho_i} + \beta_{i2}\bar{x}_{i2}^{\rho_i}}$$

which together with $\beta_{i1} + \beta_{i2} = 1$ determines the values of β_{i1} and β_{i2}, conditional on the value of δ_i obtained from one of the alternative calibration rules discussed above. It is then straightforward to derive the values of the remaining parameters α_i, μ_{i1} and μ_{i2} using the first-order conditions of program (5.1) evaluated at the reference allocation.[10]

[10] In the hybrid calibration rule, the parameters μ_{i1} and μ_{i2} are determined within the GME program.

5.4 Reference allocation

The model is calibrated to observed cropping patterns for a reference situation taken as the average of the years 2008 and 2009. Cropping patterns are constructed from a spatial database obtained from the French farm payment agency, the "Registre Parcellaire Graphique," or RPG. Acreages for Common Agricultural Policy (CAP) program crops are very well recorded; this is not the case for specialty crops such as fruits and vegetables. This lack of reliable information for specialty crops is only a minor problem in the Beauce region, because the vast majority of crops grown are eligible for CAP payments and are thus recorded in the RPG database. The advantage of the RPG geo-referenced data is that it can be aggregated to any spatial unit, in our case hydrogeologically homogeneous zones.

The years 2008 and 2009 correspond to relatively important reductions of water availability compared to the initial quotas, as the withdrawal coefficients were set at 0.45 and 0.59, respectively. The average irrigated area for these years was within long-term observed variation. The climate in 2008 was average, and the year 2009 had a wet spring but a dry summer. Likely evolutions will strengthen irrigation constraints, with a withdrawal coefficient possibly down to 0.2 (Bouarfa et al., 2011). One advantage of having an already constraining reference is that the simulations keep the model within a reasonable range. Note that our policy experiment corresponds to institutional reductions in water withdrawal, not changes in weather *per se*.

The model covers 582,500 hectares of Beauce's farmland, representing 90% of the total area registered in the RPG database. The remaining 10% include mainly set aside, pasture and orchards. Four regions are considered: (i) Beauce Centrale, (ii) Beauce Blésoise, (iii) Montargois and (iv) Fusain, each corresponding to a distinct hydrogeological area having its own water pumping restrictions according to local water policy. These regions are shown in Figure 6.1.

Yield response functions to water are constructed following the method described in section 5.3.6 based on data from Morardet and Hanot (2000), who provide yield estimates conditional on irrigation intensity for light, medium and deep soils, characterised by their field water capacity. Regional yield estimates conditional on irrigation intensity are constructed by taking into account the share of each soil type present in a given region, calculated from the EU Joint Research Center soils database (see Gardi et al. (2010)). A sigmoidal function is fitted through the generated data using NLS. Estimated coefficients are significant at the

10% level or better for each crop-region combination. Due to variation in soil type shares across regions, the yield response functions are region-specific.

We use reference irrigation levels conditional on soil type from Morardet and Hanot (2000) and update them using more recent information by Bouarfa et al. (2011). Baseline regional irrigation rates are then calculated by taking into account the share of each soil type in a region. Yield response elasticities to water for each region are computed using the fitted curves and the baseline irrigation rates according to equation (5.3).

Crop yield information is available at the administrative department level from Ministère de l'agriculture et de l'agroalimentaire (2012). This data is used to construct region-specific baseline yields. Because our yield information comes from a different source than the data used to construct the yield response functions, our reference points do not lie exactly on the yield response curves. However, for the vast majority of crop-region combinations, they are quite close. The yield response curves and baseline points are shown in Figure 5.3 for selected crops in the main region, Beauce Centrale. These curves show that irrigation intensity affects yields significantly for corn and sugar beet, but less so for other crops. Similar patterns hold in the other regions.

Expected prices of outputs for the years 2008 and 2009 are calculated based on adaptive expectations from observed prices for the years 2005 to 2008 (Pope and Just, 1991). Yearly average prices are obtained from the French statistical survey. Crop-specific production costs are calculated from Brunel et al. (2007). We distinguish between costs associated to land and those associated to water use. Fertilizer, pesticide, seed, and harvest costs are summed up to provide the variable cost of land. Farmers pay a fee amounting to €0.014 per cubic meter withdrawn from the aquifer to the basin authority. The total cost per cubic meter applied includes this fee, pumping costs and costs related to the maintenance of pumps and irrigation equipment. The total variable cost of water amounts to €0.055 per cubic meter. In 2008 and 2009, CAP direct payments still coupled to crop production in France corresponded to 25% of total direct payments and are accounted for in the objective function.

Own price-supply elasticity estimates are not available from statistical offices. For France, one of the only available data source is the estimates recently produced by Jansson and Heckelei (2011) for the CAPRI model. The advantage of this data source is that elasticities are determined for all administrative regions of Europe (NUTS II regions), for all major crops and in particular for all of the crops in our model. The fact that the elasticity information is regionalised allows for variability among the four regions under consideration.

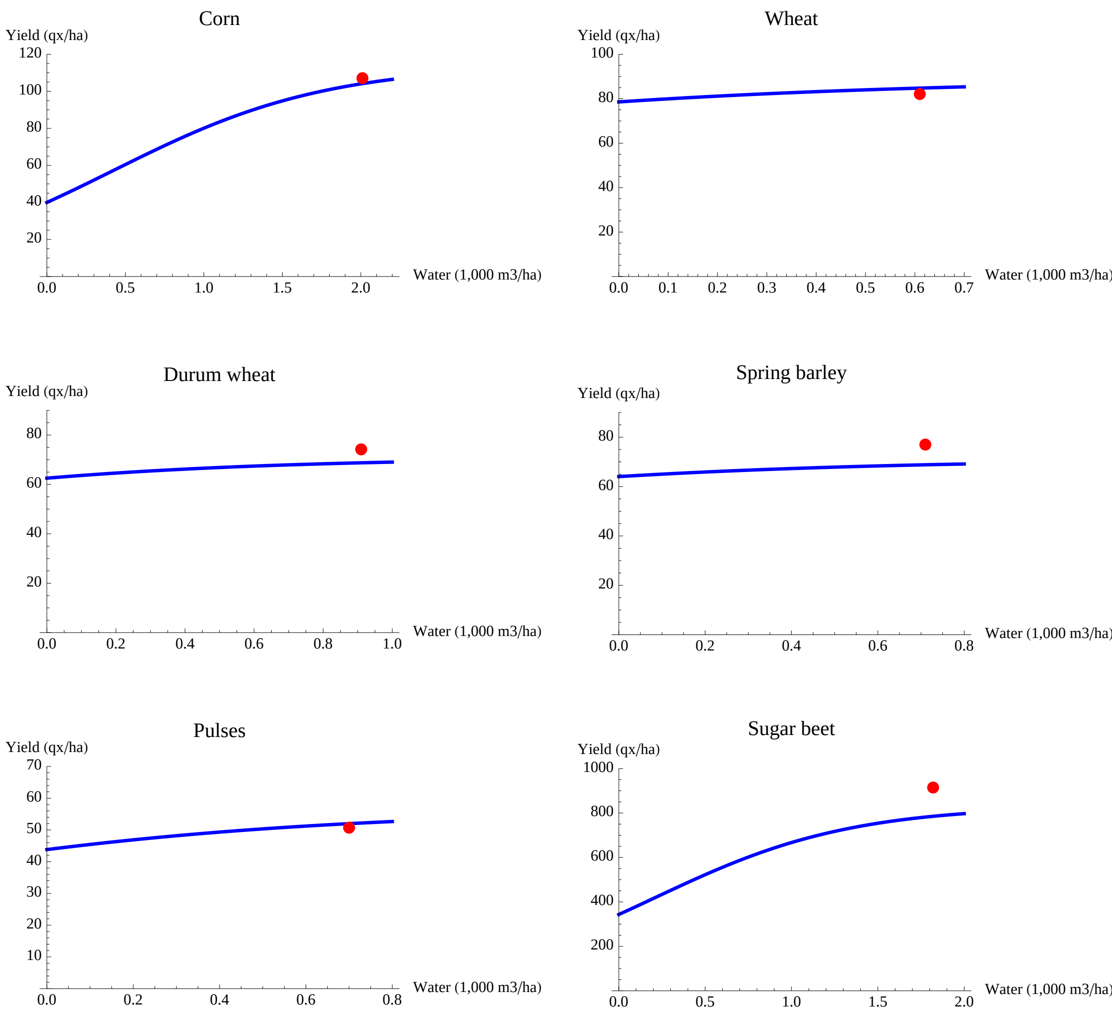


Figure 5.3: Yield response curves and calibration points for Beauce Centrale

The only shortcoming is that the data does not distinguish between irrigated and non-irrigated crops. For three out of four regions, these supply elasticities satisfy the calibration criteria for elasticity calibration. For the last region, the calibration criterion is violated, preventing calibration against the initial set of elasticities.[11] The supply elasticities are thus adjusted following the procedure described by Mérel et al. (2011). The resulting calibrated elasticities depart from the CAPRI values by less than 5%, except for the corn supply elasticity, which departs by -30%. To evaluate the sensitivity of our results to the choice of supply elasticities, we calibrate two alternative models where all target elasticities are reduced or increased by 20%. The results are reported in Appendix C, and they show that our inference is robust to the choice of supply elasticities.

The fact that each region includes both irrigated and rain fed crops implies that the land and water constraints are everywhere binding in the reference allocation, that is, they have positive shadow prices. We do not retain the shadow cost of land from the first stage of PMP as is often the case in PMP studies. The main reason is that doing so would imply that marginal activities display constant returns to scale when implementing the profit calibration rule. Models with constant-returns-to-scale activities display undesirable properties, as discussed for instance in Heckelei and Britz (2005).[12] Instead, we use available statistical information on the purchase price of arable land in each region. We recover the yearly rental price of land by assuming that the purchase price reflects the capitalisation of rents over an infinite time horizon with a 4% discount rate. In the GME calibration rule, the shadow values of water are estimated to be between 0.06 and 0.17 €/m^3, whereas the first PMP stage (for the elasticity and profit calibration rules) yields values between 0.05 and 0.14 €/m^3.

Calzadilla et al. (2011) estimate a value for the elasticity of substitution between land and water of 0.14 for Western Europe. Here we choose a conservative value of the elasticity of substitution, $\sigma_i = 0.15$, and perform sensitivity analysis along this dimension, from 0.05 to 0.25, for each of the three calibration approaches.

Table 5.1 summarises the main information used to calibrate the model.

[11]Since we later perform sensitivity analysis on the values of substitution elasticities, we use the calibration criterion for the fixed-proportions variant of our model, which, subject to myopic calibration being feasible, guarantees that calibration is feasible for *any* value of the substitution elasticities in the CES variant. See Mérel et al. (2011) and Garnache (2010).

[12]In particular, shadow prices become insensitive to marginal changes in the prices of preferred activities.

Crop	Acreage (ha)	Acreage share (%)	Yield* (qx)	Gross rev.* (€/ha)	Irrig.* (1,000 m^3/ha)	Supply elastic.*	Water-yield elastic.*
Wheat	174,571	30	78.1	1,055.3	–	0.69	–
Durum wheat	57,705	9.9	69.9	1,303.4	–	4.25	–
Rape seed	57,485	9.9	38.3	874.2	–	1.19	–
Winter barley	50,593	8.7	74.8	997.3	–	1.75	–
Spring barley	42,925	7.4	71.7	1,213.8	–	1.75	–
Irr. corn	37,904	6.5	107.1	1,290.6	2.0	1.80	0.26
Irr. wheat	26,510	4.6	83.2	1,124.2	0.6	0.69	0.05
Sugar beet	26,056	4.5	912.1	1,814.1	–	2.76	–
Irr. Durum wheat	19,361	3.3	74.2	1,383.2	0.9	4.25	0.05
Irr. winter barley	15,953	2.7	82.1	1,094.6	0.6	1.75	0.04
Irr. spring barley	13,648	2.3	77	1,303.1	0.7	1.75	0.04
Irr. Potato-Veg	11,183	1.9	532.4	4,708.8	1.9	0.93	0.22
Potato-Veg	8,342	1.4	426.5	3,772.2	–	0.93	–
Rape seed (biofuel)	7,765	1.3	38.2	764.4	–	1.19	–
Sunflower	7,748	1.3	30.5	767.3	–	3.93	–
Pulses	7,091	1.2	47.2	710.2	–	1.85	–
Corn	6,649	1.1	76.5	921.4	–	1.80	–
Irr. Sugar beet	6,473	1.1	914.6	1,819.1	1.8	2.76	0.18
Irr. pulses	4,519	0.8	50.7	762.2	0.7	1.85	0.10
Total	582,481	100	–	–	–	–	–

Table 5.1: Reference data used for calibration. (* : values for the largest region “Beauce Centrale”; crops are listed by order of importance)

5.5 Simulation

For each of the calibration rules discussed in section 5.3, we test several scenarios regarding water availability at the regional scale, each corresponding to a reduction in the withdrawal coefficient within the current water policy setting. Three scenarios are simulated, corresponding to homogeneous reductions of 10%, 20% and 30% of water availability in each region relative to the reference situation. We also implement an alternative set of scenarios allowing for transfers of water across the four regions as a mitigation strategy for reduced water availability.

5.5.1 Acreage reallocation

The simulated cropping patterns for the three calibration rules are given in Table 5.2 for the entire Beauce region and for a value of the substitution elasticity of 0.15.

The acreages of all irrigated crops decrease, while those of rain fed crops increase. For all calibration rules, irrigated corn is by far the most responsive crop. At a 30% reduction in water availability, its acreage is predicted to drop by 42% under the elasticity calibration, by

Crop	Elasticity rule		Profit rule		GME rule	
	Sc. -10%	Sc. -30%	Sc. -10%	Sc. -30%	Sc. -10%	Sc. -30%
Corn	+3%	+9%	+4%	+12%	+3%	+9%
Irr. corn	-14%	-42%	-15%	-45%	-15%	-46%
Wheat	+2%	+5%	+2%	+6%	+2%	+5%
Irr. wheat	-2%	-6%	-1%	-6%	-1%	-5%
Durum wheat	+2%	+7%	+1%	+4%	+2%	+5%
Irr. Durum wheat	-5%	-16%	-3%	-9%	-3%	-10%
Winter barley	+2%	+6%	+2%	+6%	+2%	+6%
Irr. winter barley	-2%	-8%	-2%	-7%	-2%	-6%
Spring barley	+2%	+5%	+2%	+5%	+2%	+5%
Irr. spring barley	-2%	-8%	-2%	-6%	-2%	-6%
Sugar beet	+1%	+4%	+1%	+3%	+1%	+4%
Irr. Sugar beet	-7%	-23%	-7%	-22%	-6%	-21%
Rape seed	+2%	+6%	+2%	+7%	+2%	+6%
Rape seed (biofuels)	+2%	+7%	+3%	+10%	+2%	+8%
Pulses	+3%	+9%	+3%	+9%	+3%	+9%
Irr. pulses	-4%	-13%	-3%	-12%	-3%	-11%
Sunflower	+3%	+9%	+2%	+7%	+3%	+9%
Potato-Veg	+0%	+1%	+0%	+2%	+0%	+1%
Irr. Potato-Veg	-2%	-7%	-2%	-7%	-2%	-7%

Table 5.2: Evolution of the cropping pattern without water transfers, all regions (σ_i =0.15)

45% under the profit calibration and by 46% under the GME calibration. The acreages of irrigated sugar beet, pulses and durum wheat decrease by more than 10%, while other crops seem to be less responsive to reduced water availability. Overall, the alternative calibration rules yield comparable predictions regarding acreage effects across all scenarios.

The acreage contraction pattern among irrigated crops can be better understood by deriving the relative effect of the induced changes in the shadow prices of land and water in a given region:

$$\frac{dx_{i1}}{x_{i1}} = -\frac{\bar{x}_{i1}}{p_i\bar{q}_i\delta_i}\left[\left(\frac{1}{1-\delta_i}+\frac{\sigma_i}{\frac{\delta_i}{\bar{\bar{y}}_{iw}}-1}\right)d\lambda_1+\left(\frac{1}{1-\delta_i}-\sigma_i\right)\left(\frac{\bar{x}_{i2}}{\bar{x}_{i1}}\right)d\lambda_2\right]. \tag{5.4}$$

Equation (5.4) shows that the total acreage effect is the result of two opposing effects: an expansion due to the lower price of land induced by the reduction in water availability ($d\lambda_1 < 0$) and a contraction due to the increased shadow value of water ($d\lambda_2 > 0$).[13]

If we ignore the adjustment terms due to substitution between land and water ($\sigma_i = 0$), it is clear that the sign of the acreage effect will be negative for water-intensive crops and

[13]In our application, $\sigma_i < 1$ and therefore the second term in the square bracket is always positive.

positive for water-saving crops, in particular for rain fed crops for which $\bar{x}_{i2}=0$. Indeed, the acreage effect reduces to:

$$\frac{dx_{i1}}{\bar{x}_{i1}} = -\frac{\bar{x}_{i1}}{p_i\bar{q}_i\delta_i(1-\delta_i)}\left[d\lambda_1+\left(\frac{\bar{x}_{i2}}{\bar{x}_{i1}}\right)d\lambda_2\right]. \tag{5.5}$$

Given that, in our application, the values of δ_i have comparable magnitudes for all crops, the magnitude of the acreage contraction for irrigated crops will be determined principally by (i) the water intensity $\frac{\bar{x}_{i2}}{\bar{x}_{i1}}$ and (ii) the gross revenue per hectare $\frac{p_i\bar{q}_i}{\bar{x}_{i1}}$. More specifically, irrigated activities with relatively large water intensities and relatively low gross revenues per hectare will experience greater acreage contractions. These drivers alone explain why in Beauce Centrale, corn and sugar beet experience large acreage contractions while potato, an intensively irrigated but high revenue crop, experiences a smaller contraction.

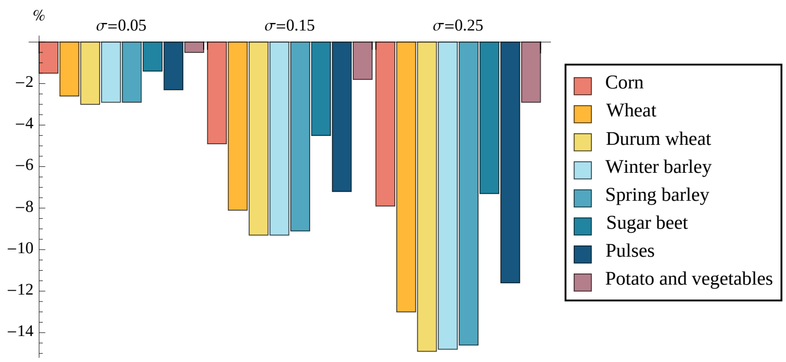
5.5.2 Deficit irrigation

The increase in the shadow value of water upon the decrease in water availability implies that the water intensity of irrigated crops decreases. Figure 5.4 illustrates these intensive margin changes in Beauce Centrale when water availability is reduced by 30%, for three alternative values of the substitution elasticity, 0.05, 0.15 and 0.25. The figure shows that the magnitude of the intensive margin adjustments increases in proportion with the substitution elasticity, and that results are consistent between the three calibration rules.

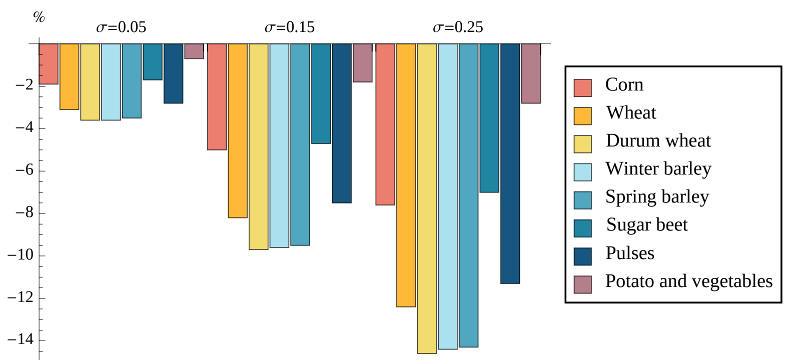
Corn, sugar beet and potato show a relatively small change in water intensity, less than 8%, while wheat (sweet and durum) and barley (winter and spring) react quite dramatically, with decreases in irrigation rates of the order of 15% for the model with $\sigma_i=0.25$. This result is in line with expectations, given that corn, sugar beet and potato have the largest yield elasticities. Therefore, reducing water intensity for those crops implies a larger decline in yield than for crops with flatter yield response curves, limiting the extent to which irrigation intensity can adjust to increased water scarcity.[14] Again, this intuition is confirmed by deriving the effects of the induced changes in shadow values on the irrigation rates:

$$\frac{d\left(\frac{x_{i2}}{x_{i1}}\right)}{\frac{\bar{x}_{i2}}{\bar{x}_{i1}}} = \left(\frac{\sigma_i}{\delta_i}\right)\left(\frac{\bar{x}_{i1}}{p_i\bar{q}_i}\right)\left[\left(1+\frac{1}{\frac{\delta_i}{\bar{y}_{iw}}-1}\right)d\lambda_1-\left(\frac{\bar{x}_{i2}}{\bar{x}_{i1}}\right)\left(\frac{\delta_i}{\bar{y}_{iw}}\right)d\lambda_2\right]. \tag{5.6}$$

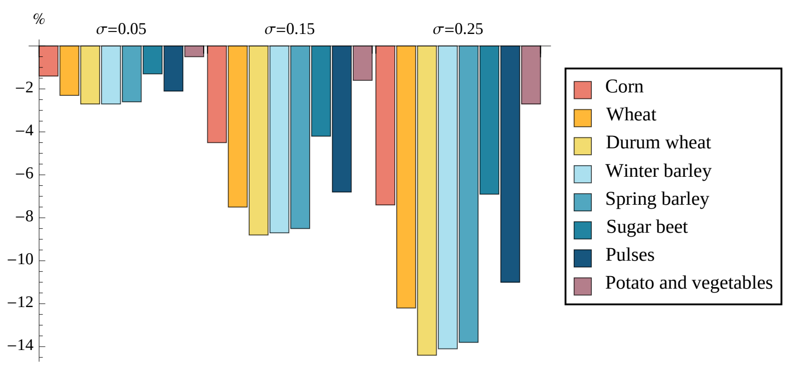
[14] This result is also in line with Bouarfa et al. (2011) and with agronomic advice from the Chamber of agriculture who suggests taking no risk on contract crops (sugar-beet, vegetables) and corn and "sacrificing," if needed, winter cereal crops (wheat and barley).



(a) Elasticity rule



(b) Profit rule



(c) GME rule

Figure 5.4: Reductions in irrigation intensity in Beauce Centrale for a 30% reduction in water availability

Equation (5.6) implies that the extent of reduction in water intensity due to the increase in the shadow price of water (ignoring the induced change in the shadow price of land) is dictated by three main factors.[15] First, the water intensity in the reference allocation: the more water intensive, the more reduction in irrigation intensity. Second, the yield elasticity with respect to water $\bar{y}_{iw}$: the more responsive the yield, the lower the reduction in irrigation. Third, the gross revenue per hectare: the higher the revenue, the lower the reduction in irrigation. These three effects alone explain the pattern of intensive margin changes for corn, sugar beet, and potato, the three activities with the largest yield elasticities to water, and consequently the ones with the lowest irrigation effects. All three crops have comparable irrigation intensities, so differences in irrigation adjustments are driven by differences in water-yield elasticities and revenue. Potato has by far the largest revenue per hectare and thus has the smallest response of all three crops. Sugar beet has a smaller yield elasticity than corn but also has a higher revenue per hectare, which explains why these two crops have comparable water responses.

Slight differences across regions, not reported here, reflect different yield responses to water according to soil characteristics.

5.5.3 Decomposition of the total effect on regional water use

The total effect of a reduction in regional water availability can be decomposed into three elementary effects. First, farmers respond by increasing the acreage in rain-fed crops at the expense of irrigated crops, the super-extensive margin effect. Second, among irrigated crops, farmers reallocate acreage away from relatively water-intensive crops towards water-saving crops, the extensive margin effect. Third, the irrigation intensity of irrigated crops decreases, the intensive margin effect.

The decomposition can be formalised as follows. Denote by X_2 the total water use at the regional level, where again the regional index is omitted for notational simplicity. Further denote by I the set of all crops and by $I_W \subset I$ the set of irrigated crops. Denote $X_{1W} = \sum_{i \in I_W} x_{i1}$, and, for $i \in I_W$, $s_{iW} = \frac{x_{i1}}{X_{1W}}$ and $w_i = \frac{x_{i2}}{x_{i1}}$.

[15]In our application where irrigated crops all have relatively high ratios $\frac{\delta_i}{\bar{y}_{iw}}$, the term associated with the change in λ_1 turns out to be fairly comparable across crops. Since we assume here that the substitution elasticity σ_i is identical for all crops, this parameter does not explain differences in irrigation response across crops.

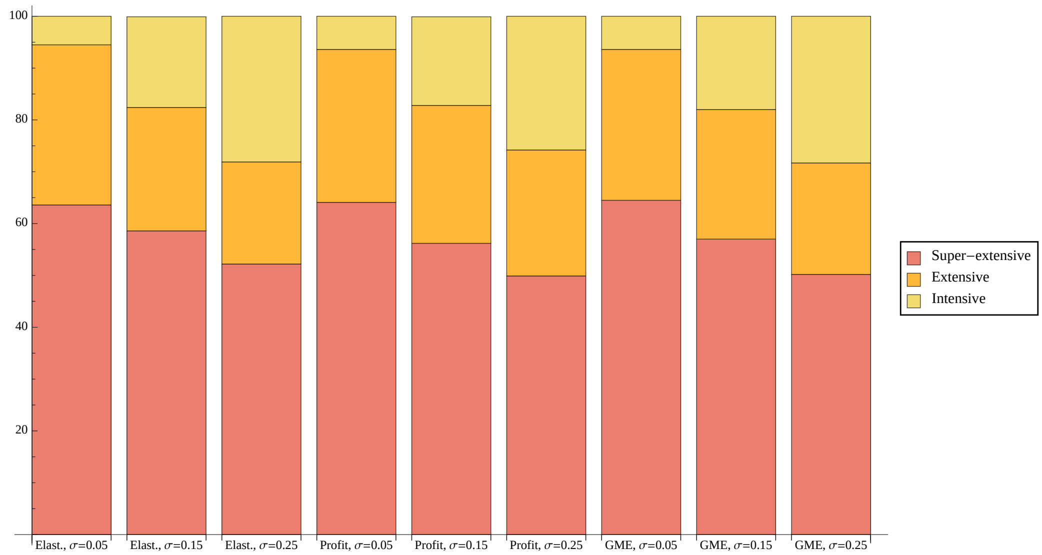


Figure 5.5: Relative importance of adjustment margins for a 30% reduction in water availability

We have that $X_2 = \sum_{i \in I_W} x_{i2} = \sum_{i \in I_W} x_{i1} w_i = X_{1W} \sum_{i \in I_W} s_{iW} w_i$. Therefore, the total effect of a marginal change in regional water availability can be decomposed as:

$$dX_2 = \underbrace{dX_{1W} \sum_{i \in I_W} s_{iW} w_i}_{\text{super-extensive margin}} + \underbrace{X_{1W} \sum_{i \in I_W} w_i ds_{iW}}_{\text{extensive margin}} + \underbrace{\sum_{i \in I_W} x_{i1} dw_i}_{\text{intensive margin}} .$$

The decomposition is illustrated in Figure 5.5 for a 30% reduction in water availability, under the three calibration rules and for three values of the elasticity of substitution, 0.05, 0.15 and 0.25. The figure reflects water reductions across all regions. Region-specific decompositions look very similar and are not reported here.

Super-extensive adjustments represent almost 60% of the total effect for each calibration rule, for a substitution elasticity of 0.15. Increasing the substitution elasticity to 0.25 decreases this contribution to about 50% and increases the relative contribution of the intensive margin adjustments by about 10%. Extensive margin adjustments account for about 25% of total water savings. Overall, the nine tested models are consistent with each other regarding the ranking of the contributions of the three margins to the reduction in regional water use. The main source of variation across models is the chosen value of the substitution elasticity, which dictates the reductions in irrigation rates, as indicated in equation (5.6). Decompositions of the adjustment margins under the water scenarios -10% and -20% are qualitatively close, with relative contributions within 2% of those reported in Figure 5.5. Therefore, the contributions of the adjustment margins do not seem to be affected by the magnitude of the reduction considered.

These results clearly suggest that the most critical adjustment margins to water scarcity in Beauce are the super-extensive and extensive margins. Together, they comprise between 72% and 95% of the total adaptation to water scarcity, depending on the model considered. This finding is consistent with other empirical works on the Beauce region (Bouarfa et al., 2011; Lejars et al., 2012). Qualitatively, it is also in line with earlier findings by Moore et al. (1994) for the Western United States that suggest that water price affects crop choice and land allocations but has no clear effect on input intensities at the crop level. One difference, however, is that our results indicate that adjustments on the intensive margin are not negligible, despite the relatively modest share of irrigated agriculture in the Beauce region, as they represent between 5% and 28% of the total response.

In contrast to these results, Frisvold and Konyar (2012) find that a 25% reduction in water availability in the Southern Mountain states of the United States is achieved in large part by a reduction in the irrigation intensities of alfalfa, cotton, wheat, corn and barley, suggesting a dominant contribution of the intensive margin adjustment.[16] More recently, Hendricks and Peterson (2012) use field-level panel data from Kansas to decompose the demand elasticity for irrigation water into elementary contributions similar in nature to our three margins, and find that the intensive margin represents most of the response to water price changes.[17]

5.5.4 Output effects

The effects of water scarcity on outputs are in line with the effects on acreages. Looking at output effects allows us to envision the effect of water scarcity on commodity production at the regional scale, which may be important for the local transformation industry. Here we ignore the way commodities are produced (irrigated or rain fed). Table 5.3 shows the output effects for all three calibration rules, assuming an elasticity of substitution of 0.15. In the -30% scenario, corn output is reduced by about -35%, a very important decrease that might affect the corresponding local transformation industry. Other crops are less affected, except

[16] Connor et al. (2009) in a study on the economic impact of climate change on irrigation in Australia found that both intensive and extensive adjustments would take place in the Murray-Darling basin, but they do not quantify the relative contributions of such responses.

[17] These authors use a different terminology than ours. Their direct intensive, indirect intensive and extensive margins correspond to our intensive, extensive and super extensive margins, respectively.

Crop (irrigated and rain fed)	Reference (1,000 T)	Elasticity rule		Profit rule		GME rule	
		Sc. -10%	Sc. -30%	Sc. -10%	Sc. -30%	Sc. -10%	Sc. -30%
Corn	454.5	-10.9%	-33.3%	-11.7%	-35.4%	-12.2%	-37.0%
Potato-Veg	957.1	-0.6%	-2.2%	-0.6%	-2.1%	-0.8%	-3.1%
Sugar beet	2 973.2	-0.4%	-1.4%	-0.5%	-2.0%	-1.3%	-5.6%
Pulses	56.7	+0.1%	-0.3%	-0.0%	-0.6%	+0.6%	+0.6%
Durum wh.	538.9	+0.3%	+0.6%	+0.1%	-0.1%	+0.3%	+0.6%
Spring barley	411.1	+0.4%	+1.0%	+0.2%	+0.6%	+0.5%	+1.4%
Winter barley	499.4	+0.6%	+1.7%	+0.4%	+1.2%	+0.7%	+2.0%
Sweet wh.	1 555.7	+0.6%	+1.9%	+0.6%	+1.8%	+0.6%	+1.9%
Rape seed	218.1	+1.2%	+3.7%	+1.5%	+4.8%	+1.2%	+3.7%
Rape seed (biofuel)	29.3	+1.3%	+4.1%	+2.3%	+7.5%	+1.3%	+4.2%
Sunflower	22.5	+2.2%	+7.1%	+1.1%	+3.6%	+2.2%	+7.2%
Total	7 716.5	-0.6%	-2.1%	-0.7%	-2.5%	-0.6%	-2.1%

Table 5.3: Evolution of output without water transfers, all regions (σ_i =0.15)

rape seed and sunflower, which show a sizable increase in production. Overall, results are consistent between the three calibrated models.

5.5.5 Agricultural profits

Although the water availability reduction scenarios are arguably quite drastic, agricultural profits do not seem to be affected by much.[18] Table 5.4 shows the relative reductions in the objective function under each scenario considered for the various models tested. Models calibrated using the profit rule display reference profits equal to accounting profits. This is not the case for models calibrated using the elasticity rule or the GME rule.

The fact that profits are only moderately affected by water reductions is mainly due to the fact that irrigated crops cover a relatively modest share of total acreage, about 23%. In addition, substitution possibilities between water and other inputs for irrigated crops imply that some of the reduced water availability can be absorbed by reductions in irrigation rates. For a 30% reduction in water availability, regional agricultural profits decrease by only 1.10%. In absolute terms, this decrease represents a loss of about €4.5 million per year. Even though profits are different in absolute value for the three calibration rules, the relative changes are comparable between models. This result suggests that profit analysis can be performed with confidence using the value function even when baseline profit levels are not replicated exactly, like under the elasticity or GME calibration rule. Reductions in

[18]These profits exclude decoupled direct payments as these are, to a large extent, independent from production.

Profit in million €		Reference	Sc. -10%	Sc. -30%
$\sigma = 0.05$	Elasticity rule	413.1	-0.29%	-1.07%
	Profit rule	472.7	-0.26%	-0.99%
	GME rule	429.0	-0.45%	-1.51%
$\sigma = 0.15$	Elasticity rule	416.5	-0.29%	-1.10%
	Profit rule	472.7	-0.25%	-0.96%
	GME rule	429.5	-0.38%	-1.33%
$\sigma = 0.25$	Elasticity rule	418.9	-0.29%	-1.09%
	Profit rule	472.7	-0.25%	-0.94%
	GME rule	429.9	-0.33%	-1.18%

Table 5.4: Profit effects

profit for the GME rule are slightly more important than for the elasticity and the profit rule, likely because of different reference shadow values for water.[19]

5.5.6 Sensitivity analysis on the substitution elasticity

From the sensitivity analysis covering values of σ_i from 0.05 to 0.25, we observe modest variation in results. This lack of sensitivity is notable on the profit effects (Table 5.4). However, the three models are not equally sensitive to the value of this parameter. Indeed, profits in the GME rule display small variations with respect to the substitution elasticity, whereas the elasticity and profit rules show nearly no variation. The reason for this is that in the GME rule, the shadow value of water is determined without using the first stage of PMP, and it thus depends on the choice of substitution elasticity.

The substitution elasticity parameter has, as expected, a non negligible impact on water application intensities (Figure 5.4) and on the relative contributions of adjustment margins to the reduction in water availability (Figure 5.5). This effect seems to be very similar for each of the three models analysed here.

[19] Recall that the GME model also elicits the shadow values of water instead of recovering them from the PMP first-stage.

5.5.7 Reduction in water availability with water transfers

Water transfers among regions represent a potential mitigation strategy to water scarcity, since allowing water to flow from low value regions towards high value regions improves the overall economic performance of agriculture.

The results from simulating a reduction in water availability of 30% over the entire region while allowing water transfers among regions are reported in Table 6.2. As regions show very different shadow values of water in the reference situation, the model simulates water transfers from regions with relatively low shadow values (Beauce Centrale and, depending on the calibration rule considered, Beauce Blésoise) towards regions with higher shadow values (Fusain and Montargois). Under the elasticity and profit calibration rules, water use in Fusain and Montargois is predicted to increase by more than 50% relative to the situation without transfers. This additional water is used to increase irrigation rates from 1% to 9% above the reference rates and to support an acreage expansion of irrigated agriculture by about 30% in Fusain and Montargois (elasticity rule, $\sigma = 0.15$.) We believe these water transfers to be realistic as the water resource is the Beauce aquifer, which is a homogeneous water body even if different hydrogeological zones can be distinguished. Therefore, such transfers could be implemented through changes in water withdrawal policy without additional infrastructure costs.

Yet, such transfers compensate only 6% of the economic losses due to the reduction in water availability. The average benefit of transfers is estimated to be between 3 and 4 cents per cubic meter transferred under all three calibration rules.

As transfers are determined based on the dual values of water in each region, under the GME rule the pattern of water transfers is somewhat different than under the other calibration rules, due to different reference shadow values for water. Yet, we note that the signs of the transfers are comparable with those of the profit rule.

These results should be considered together with hydrogeological information to assess the opportunity of a more flexible water quota scheme among regions.

5.6 Conclusion

Efficient water management in agriculture is becoming critical due to increasing environmental constraints and global food and bioenergy demands.

		Beauce Blésoise	Beauce Centrale	Fusain	Montargois
Elasticity rule					
Water use	W/o transfers	7,763	96,568	3,128	8,539
(1,000 m^3)	With transfers	8,315 (*+7%*)	89,506 (*-7%*)	4,856 (*+55%*)	13,321 (*+56%*)
Dual value	W/o transfers	140	115	211	202
(€/1,000 m^3)	With transfers	130			
Profit rule					
Water use	W/o transfers	7,763	96,568	3,128	8,539
(1,000 m^3)	With transfers	7,209 (*-7%*)	90,063 (*-7%*)	5,050 (*+61%*)	13,675 (*+60%*)
Dual value	W/o transfers	124	117	185	180
(€/1,000 m^3)	With transfers	132			
GME rule					
Water use	W/o transfers	7,763	96,568	3,128	8,539
(1,000 m^3)	With transfers	6,380 (*-18%*)	94,724 (*-2%*)	3,366 (*+8%*)	11,528 (*+35%*)
Dual value	W/o transfers	119	143	161	187
(€/1,000 m^3)	With transfers	146			

Table 5.5: Water use and dual values with and without transfers under the -30% water availability scenario ($\sigma = 0.15$)

This work represents the first attempt to calibrate a relatively large-scale PMP model of regional agricultural supply using, in addition to traditional information on crop budgets, acreage decisions, and supply elasticities, agronomic crop yield responses to water, in order to decipher the relative contributions of the super-extensive, extensive, and intensive margin adjustments to water scarcity.

We find that in the context of the Beauce region, the contributions of the extensive and super-extensive margins, which capture acreage reallocation effects, dominate the total response to water scarcity. However, intensive margin adjustments, capturing deficit irrigation, are far from being negligible. These results suggest the need to better account for irrigation intensity adjustments in large-scale programming models of agricultural supply, particularly in water-constrained regions, whenever scenarios involving decreased water availability are being investigated. Since the calibration method we use depends critically on the availability of agronomic information, in the form of yield response elasticities to input intensity, these results emphasise the need to produce such information in a more systematic manner and at a scale commensurate with that of the assumed decision-making unit.

Our finding that extensive and super-extensive adjustments dominate intensive adjustments in the case of water scarcity in Beauce is in contrast with recent findings by Mérel et al. (2013), who use a PMP model similar in structure to analyse the effects of a nitrogen tax on nitrogen employment in Yolo County, CA, USA. These authors find that at low to moderate tax levels, the bulk of the reduction in regional nitrogen application is due to intensive margin adjustments. Therefore, it is clear that whether intensive or extensive margin effects dominate the input employment response is not driven by the assumed model structure—crop-specific CES production functions with decreasing returns to scale and moderate elasticities of substitution—but instead by the economic and agronomic information utilised to calibrate the model. In our view, this is a reassuring finding.

Another methodological contribution of this work was to compare three PMP variants based on their responses to water availability scenarios. Although the three variants calibrate to different sets of economic information (supply elasticities vs. accounting profits) and one of them no longer relies on the first stage of PMP, we found their predictions to be very close in all simulations. This result is also reassuring.

From a policy perspective, our results indicate low aggregate costs of adaptation to water scarcity in Beauce. This finding is attributable to the modest share of irrigated agriculture, the relatively large number of irrigated crops, and the possibility of deficit irrigation without much yield loss on certain crops. These factors are directly related to the three adjustment margins discussed above. This large potential for adaptation involves a large predicted drop in corn output, however. In addition, we find only low benefits from allowing water transfers across regions.

The methodology proposed here could be used for several applications. The first would be to explore the effects of reductions in water availability on agriculture as a consequence of policy, as illustrated with our case study, or as a consequence of climate change.[20] A second type of application would be the simulation of global change scenarios (joint increase in product prices, policy changes such as the CAP reform and reduction in natural water availability). The methodology could also be applied to economic modules within larger hydro-economic modeling approaches, which are increasingly used to address water scarcity problems.

[20] Climate change might induce a reduction of less than 20% runoff (i.e. of the water resource) in Central and Eastern Europe (Milly et al., 2008). As such, its impact can be safely assessed by PM methods that are suited to simulate reasonable changes in model parameters—as opposed to very large changes.

Appendix A: Elasticity calibration system

Garnache (2010) have derived the implied supply elasticity of activity i in a CES model with multiple inputs and two resource constraints. Adapting their notation to that of the present article with two inputs and two constrained resources and defining $\bar{b}_i = \frac{\bar{x}_{i1}^2}{p_i \bar{q}_i}$, we obtain the implied elasticity of supply of crop i at the reference allocation as

$$\eta_i = \frac{\delta_i}{1-\delta_i}\left[1 - \frac{\mathcal{N}_i}{\mathcal{D}\delta_i(1-\delta_i)}\right]$$

where

$$\mathcal{N}_i = \sum_{j\neq i} \frac{\bar{b}_i \bar{b}_j (\bar{w}_i - \bar{w}_j)^2}{\delta_j(1-\delta_j)} + \sum_{j=1}^{I} \frac{\sigma_j \bar{b}_i \bar{b}_j}{\delta_j}\left(\frac{\bar{w}_i}{\sqrt{\frac{\delta_j}{\bar{y}_{jw}}-1}} + \bar{w}_j\sqrt{\frac{\delta_j}{\bar{y}_{jw}}-1}\right)^2$$

and

$$\mathcal{D} = \left(\sum_{j=1}^{I} \frac{\bar{b}_j}{\delta_j(1-\delta_j)} + \frac{\sigma_j \bar{b}_j}{\delta_j\left(\frac{\delta_j}{\bar{y}_{jw}}-1\right)}\right)\left(\sum_{j=1}^{I} \frac{\bar{b}_j \bar{w}_j^2}{\delta_j(1-\delta_j)} + \frac{\sigma_j \bar{b}_j \bar{w}_j^2\left(\frac{\delta_j}{\bar{y}_{jw}}-1\right)}{\delta_j}\right) - \left(\frac{\bar{b}_j \bar{w}_j}{\delta_j(1-\delta_j)} - \frac{\sigma_j \bar{b}_j \bar{w}_j}{\delta_j}\right)^2.$$

Appendix B: Structure of the GME program

Each region is treated independently, therefore we drop regional indices. Denote by $\bar{\pi}_i$ the baseline profit of crop i, defined as $\bar{\pi}_i = p_i\bar{q}_i - c_{i1}\bar{x}_{i1} - c_{i2}\bar{x}_{i2}$. The GME calibration rule sets model parameters so as to solve:

$$\max_{\substack{s_{i1}, s_{i2} \\ \eta_i, \delta_i, \mu_{i1}, \mu_{i2}, \bar{\lambda}_2}} \quad -\textstyle\sum_{i\in I}\sum_{k=1}^{2}\left[s_{ik}\ln s_{ik} + (1-s_{ik})\ln(1-s_{ik})\right]$$

$$\text{subject to} \quad \begin{cases} \eta_i = s_{i1}\bar{\eta}_i(1-0.70) + (1-s_{i1})\bar{\eta}_i(1+0.70) \\ \mu_{i1}\bar{x}_{i1} + \mu_{i2}\bar{x}_{i2} = s_{i2}\bar{\pi}_i(1-0.35) + (1-s_{i2})\bar{\pi}_i(1+0.35) \\ \eta_i = \frac{\delta_i}{1-\delta_i}\left[1 - \frac{\mathcal{N}_i}{\mathcal{D}\delta_i(1-\delta_i)}\right] \\ p_i\bar{q}_i(\delta_i - \bar{y}_{iw}) = (c_{i1} + \mu_{i1} + \bar{\lambda}_1)\bar{x}_{i1} \\ p_i\bar{q}_i\bar{y}_{iw} = (c_{i2} + \mu_{i2} + \bar{\lambda}_2)\bar{x}_{i2} \end{cases}$$

where $\mathcal{N}_i$ and $\mathcal{D}$ are defined in Appendix A.

		Baseline	Sensitivity analysis	
		η_i	η_i+20%	η_i-20%
Profit	Reference in million €	417	389	451
	Evolution	-1.10%	-1.13%	-1.06%
Margins	Super-extensive	59%	53%	59%
	Extensive	24%	21%	22%
	Intensive	18%	26%	20%
Acreage effects	Corn	+9%	+9%	+8%
	Irr. corn	-42%	-44%	-40%
	Wheat	+5%	+5%	+6%
	Irr. wheat	-6%	-5%	-8%
	Durum wheat	+7%	+8%	+6%
	Irr. Durum wheat	-16%	-16%	-17%
	Winter barley	+6%	+6%	+6%
	Irr. winter barley	-8%	-7%	-9%
	Spring barley	+5%	+5%	+5%
	Irr. spring barley	-8%	-7%	-9%
	Sugar beet	+4%	+4%	+4%
	Irr. Sugar beet	-23%	-22%	-24%
	Rape seed	+6%	+6%	+7%
	Rape seed (biofuels)	+7%	+7%	+8%
	Pulses	+9%	+9%	+9%
	Irr. pulses	-13%	-12%	-14%
	Sunflower	+9%	+9%	+9%
	Potato-Veg	+1%	+1%	+2%
	Irr. Potato-Veg	-7%	-6%	-8%

Table 5.6: Sensitivity analysis on supply elasticities under the elasticity rule, Sc. -30%

Appendix C: Sensitivity analysis on supply elasticities

The following table shows the main results from a model calibrated under the elasticity rule with different sets of supply elasticities. In these simulations, $\sigma_i = 0.15$ and the water reduction scenario is -30%.

Chapter 6

Trade-offs between irrigated agriculture and groundwater level for alternative water policies in Beauce (France)

[1]

[1]This research has been initiated within the BRGM project MODELECO dedicated to hydro-economic modeling approaches and has received support from the Scientific Direction of BRGM. I thank Susanne Schomburgk for the hydrogeological zoning, data collection and editing and discussions on the hydrogeological module. I thank Frederic Verley (DREAL - Région Centre) for early and encouraging discussions on this work, JD Rinaudo (BRGM) for valuable comments on an earlier version, JC Marechal (BRGM) for helpful comments on the hydrogeological model and Yvan Caballero (BRGM) for insights on climatic scenario modeling.

6.1 Introduction

Costs and effectiveness of water policies can be interesting to be considered jointly, as recommended by the Water Framework Directive through the use of a cost-effectiveness ratio (WATECO–CIS Working Group, 2003). The cost-effectiveness ratio gives the total annual cost per additional meter of groundwater drawdown for different measures or policies and represents both the effect of reduced water availability on farming and the effect of withdrawals on the water resource. It enables to compare several alternative policies from both the economic and environmental point of view. The costs or benefits of policies and global change evolutions on farming can be assessed with calibrated economic programming models such as those developed in the precedent chapters. To assess the effectiveness of water policies and the subsequent state of water resources, there is a need to represent the inpact of water uses on water resources. As underscored by Berbel et al. (2011) the pressure of an activity (extraction of water or pollution load at the ground level) must not be confounded with the impact[2] of an activity that can be measured by looking at the water resource or ecosystem considered (i.e. the level of an aquifer, the flow in a river or even the ecological state such as the fish population in a river), and the latter should be used in CEA, because the real impact is of importance more than the pressure. This calls for connecting a bio-physical representation of the system i.e. hydro-geologics or hydrologics with economics in the case of quantative water management when irrigated farming is a large water user. Modeling both the hydro(geo)logic system together with the economic and regulation system is often refered to as hydro-economic modeling (Harou et al., 2009). Heinz et al. (2007) also suggests that these models can be an opportunity to respond to the challenges of the Water Framework Directive.

Another rationale for considering, together, the economics and bio-physics of water resource dynamics is when the regulation (i.e. water rights or water restrictions) is a function of water resources state. In this case it is also necessary to adopt a systemic approach to explore the evolution and adaptation of the hydro-economic system. To represent the real-world, calibration is required in order to reduce the distance between the model reference situation replication and the observed situation. However, hydro-economic models include

[2]These two termes "pressure" and "impact" refer to the DPSIR *Driver-Pressure-State-Impact-Response* scheme, a well known integrated assessment method commonly referred to in the Water Framework Directive implementation studies

rarely economic and hydro(geo)logical models that are calibrated (Cai and Wang, 2006), as we suggest here.

In this last chapter, we will demonstrate the interest of holistic calibrated hydro-economic modeling in the perspective of comparing alternative instruments. The underlying research question is "Can we differentiate recommendations on the choice of an instrument in the context of agricultural groundwater extraction depending on the groundwater characteristics?". We will still focus on the Beauce case, which is an illustration of irrigated farming that relies on groundwater resources with individual regulated access to groundwater via wells. In this case, there are several externalities and constraints that link the economic agents with the resource. These justify the interest of hydro-economic modeling that include a representation of both the economic system -the farming sector - and the groundwater resource quantitative state.

A holistic hydro-economic model that connects a detailed calibrated economic model with a hydrogeological model is designed. Its aim is to simulate the adaptation of the system to various water management alternatives that could be envisioned in the implementation of the water governance reform implied by the french Water law and that might lead to reconsider the existing water quota system. Climate related uncertainty (precipitations' and water crop needs) is also considered. We test two extreme scenarios to show the effects of a regulation over no regulation at all and to show the impact of the resource of a total stop of irrigation. To this aim we integrate within a unique modeling plateform an economic model such as the one discussed in the previous chapter and an hydrogeological model which represents a piezometric head function which accounts for recharge, drainage and withdrawals.

The issue here was to satisfy both the challenge of representing real-world biophysical and economic processes of hydrogeology and agriculture respectively with their spatial and temporal variability, and the challenge of conceptualizing generic indicators to evaluate alternative water policies including the options of open access of the resource. As such it joins another more analytical and theoretical litterature that is concerned with optimality of control over no control of the resource detailed later on.

It is also, to the extend of our knowledge, the first attempt to represent in a unique calibrated model both a groundwater resource and irrigated farming behaviour in France.

The remaining of this chapter is organized as follows: The first section details the governance issue given that the actual governance has been detailed in Chapter 5, the second presents the hydro-economic model and the calibration of both sub-models. Last, results are presented and then discussed for five management alternatives and two extreme cases (no regulation and stop of irrigation).

6.2 Groundwater governance reform in the Beauce region

As detailed in Chapter 1 irrigation water withdrawals are regulated according to the state of water resources (i.e. piezometric levels). However, this regulation scheme has not proven to be totally efficient, as restrictions have been taken in summer 2011. The local SAGE de Beauce (Water Management Plan), which perimeter has been determined in 1999, is about to be adopted and several measures are under study. The objectives of the SAGE are to determine the principles, means and goals to reach a balanced and sustainable water quality and quantity and to maintain the good state of natural ecosystems. It includes the adaptation of the water withdrawals regulation which control will be delegated to the future “organisme unique”. The Beauce aquifer has also been classified as a "Zone de Répartition des Eaux", an important instrument of the French Water Law to comply with the European Water Framework Directive (WFD). This classification implies that all withdrawals are submitted to prior governmental authorization because there is a need to manage the quantitative groundwater state. The overall objective is to have a good structural governance that avoid crisis situations and thereby any crisis management and constraints for the farmers that are very difficult to handle on a short time basis (an irrigation restriction in summer, after crops are already grown might be more costly than the same restriction known at the beginning of the growing season). One of the debated options to be adopted by the SAGE is to restrict more the eastern part of the territory (Montargois & Fusain), but more regulations principles could be thought of. We will assess the cost and effectiveness of alternative instruments to show their relevance.

6.3 Current approaches in hydro-economic modeling

The rising concern on the need to coordinate economic policies and environmental policies, calls for a global comprehension about the interaction between the socio-economic world and the bio-physical functioning of water resource and related eco-systems. Hydro-economic modeling is a pragmatic answer to the need to represent the whole bio-physical and economic system. The aim of such model development is to understand and simulate alternative management schemes in often water - conflicting areas or when water causes damages such as floods (Jonkman et al., 2008).

A first type of models can be qualified as analytical models, typically these models are non-calibrated. They are rarely defined as *hydro-economic models* in the literature and adopt a social planner perspective. In these works the central question is the optimal control of temporal groundwater allocation of water from a social point of view, even if this optimum is far from the private optimum that might be closer to the real observed allocation. Some examples are provided by Burt (1964); Rubio and Casino (2001); Koundouri (2004b); Koundouri and Christou (2006). They are often concerned with the so-called Gisser-Sanchez effect (GSE) that states that optimal control (i.e. temporal management) of the resource does not provide significant benefits over the non regulated, myopic case[3] (Gisser and Sãnchez, 1980). However, conditions in which it applies are very restrictive from an hydrogeological point of view: the model are relatively simple and the storativity coefficient has to be important. Some of these works have also explored the effects of instruments such as markets (Provencher and Burt, 1994) or cooperation between stakeholders (Esteban and Albiac, 2011). In addition, the majority of analytical models lack realism and thus are difficult to exploit for applied decision making.

More empirical approaches to hydro-economic modeling are concerned with the effect of instruments on the hydro-economic system (e.g. Ward and Pulido-Velazquez (2007); Pena-Haro et al. (2010); Balali et al. (2011)) or with the estimation of the economic value of water (Medellìn-Azuara et al., 2009; Pulido-Velazquez et al., 2008), and not anymore with the question of the optimal control. In other terms, their aim is more to stick to the representation of real economic processes without considering whether the water use is optimal from a social planners' perspective over the long term. This is also our perspective in the present work.

Among applied hydro-economic models, the main distinction that can be made is the compartment versus holistic approach. Holistic modeling[4] gathers both the economic and biophysic characterizations (equations) under a unique control program and the two sub-models can be solved simultaneously (e.g. Cai et al. (2003); Rosegrant et al. (2000); Medellìn-Azuara et al. (2009)). This enables multiple feedbacks and relations between the different hydrologic and economic variables. In these cases, some of the sub-models are often sim-

[3]The term myopic refers to a behaviour that accounts for short term only, e.g. the year instead of considering a multiple period optimization

[4]also sometimes refered to as *integrated modeling*, but this terminology can be ambigously assimilated to any type of interdisciplinary modeling

plified. The other approach can be called the compartment or modular approach (see e.g Lefkoff and Gorelick (1990); Graveline et al. (2013)). It consists of gathering separate models (each of the compartments) in different softwares that exchange variables; for instance, one hydrological, one agronomic (crop growth), one reservoir and one (economic) farm module that are coupled with each other. In the compartment approach links between module are realized with data exchange (output of one is the input of the other). The main advantage is that each module can be specified and build in different software's, that might be more adapted to each. GIS (Geographical Information System) coupling is also possible for spatial representation of results. The major drawback is that data exchange between modules can be hard to handle when iterations are numerous. Pure optimization is not really possible unless extra-programs handle the iteration and exchanges; time needed for solving might be a drawback too.

In the majority of cases there is also no detailed representation of the hydrogeological processes and variability, except for a few very large hydro-economic compartment models in Spain (developments around the Aquatool model, Pulido-Velazquez et al. (2006)) and in the United States (CALVIN model, Howitt et al. (2010)). Hydro-economic models have extended over the last ten-twenty years and examples can be found all over the world as quoted by Varela-Ortega et al. (2011). Empirical hydro-economic models have been reviewed by Heinz et al. (2007); Brouwer and Hofkes (2008); Harou et al. (2009).

6.4 Model

6.4.1 Overview of the Beauce hydro-economic model

The main advantage that justifies the choice of a holistic hydro-economic model, as opposed to a compartment model is that it facilitates the exchange of input & output parameters between models which enables, in our case, a convenient multiple year simulation. It also enables for numerous policy or scenario simulation, which is also an advantage when working with stakeholders. Three main dynamic connections between the economic and hydrogeological models are represented in our model: (i) the irrigation water withdrawal is used to calculate the piezometric head of the aquifer, (ii) the yearly regulatory constraints are a function of the piezometric head level, (iii) the cost of water for farmers is a function of the depth of the aquifer. This last link can be considered as an internalized externality: the more the farmers pump, the deeper the piezometer level gets, the more expensive the cost of water provision gets and the lower their water quota for the following year gets.

The time scale of the model is yearly. A hydrologic year starts on the 1st of April of each year, and this is assumed to be the date when piezometric levels are observed to derive the yearly coefficient.[5] Sustainability of the hydrogeological system is ensured when the hydrogeological balance keeps the piezometric levels above a threshold over a multiple year period.

We build a dynamic recursive model in the sense that the optimization of the economic maximization function is realized on a yearly basis (n), but it includes constraints based on year $n-1$ piezometric head level. As such, it corresponds to a multi-period simulation without inter-temporal optimization.[6]

In simulation the yearly withdrawal coefficient are first calculated according regional determined piecewise linear functions that give the coefficient in function of the piezometric level h_n (See Appendix 6.8 for one of the regional function that links the piezometric level and the yearly coefficient). Then, the economic model runs to represent the behaviour of farmers in terms of cropping patterns and water allocation decisions at the beginning of the agricultural season regarding the yearly water availability. Note that even if some crops have to be sown before the farmers know exactly the yearly coefficient, we assume, based on expert advice, that the knowledge of the state of the aquifer is such that the cropping pattern would not be changed (re-optimized) after the 1st of April.[7] Then, weather conditions that occur during late spring and summer are randomly and independently drawn from past conditions that are classified among dry, medium and wet conditions. These will determine the recharge of the aquifer, the real water application on crops and the resulting withdrawals, conditional on the planned, likely deficit, irrigation at the beginning of the campaign. Then the hydrogeological model simulates the resulting year $n+1$ piezometric head level and natural drainage.

[5] In reality this date is variable but is always in March or April

[6] Inter-temporal optimization is a multi-time period optimization. This can be interesting for mainly two settings: the first being the farmers' decision upon growing perennial crops, e.g. Balali et al. (2011); Connor et al. (2012) and the second being the social planners perspective that maximizes over a long time period. Thus we assume here that farmers are *myopic* and do not account for the following years input allocation, because they grow annual field crops.

[7] The farmer already knows before the official date, the order of magnitude of the yearly coefficient through a dedicated internet site information. If there would be a significant amount of extra-information on water availability valued after the beginning of the seeding campaign a two or more step model would be required. These models are referred to as discrete stochastic programming models (Rae, 1971a), an example of application is Dono et al. (2010). See Chapter 2 for a description.

A cost-effectiveness indicator is calculated from the results of the hydro-economic model to compare different management alternatives. The reference here (indexed $_0$) refers to a case with no-regulation. We define the CEA indicator in the following way:

$$Cea_{n,r,Sc} = \frac{\pi_{n.0} - \pi_{n.Sc}}{S_r * (h_{n.r.Sc} - h_{n.r.0})}$$

$$CEA_{Sc} = \frac{\sum_r \left[S_r * \sum_n \frac{1}{1+\gamma^n} * Cea_{n,r,Sc} \right]}{\sum_r S_r}$$

with $\pi_{n.o}$ the economic profit of agriculture in year n in the no-regulation case and $\pi_{n.Sc}$ the profit for a given scenario, S_r the area in region r, h_n the piezometric level and γ the discount rate (4%).

Note that this indicator is an average cost-effectiveness ratio (and not a marginal one). The interpretation of the results have to be drawn carefully, because a policy that will reach higher piezometric levels can have a higher cost-effectiveness ratio and still be relevant to be selected because it will enable to reach higher environmental effectiveness. In fact, the comparision of this ratio can be done with confidence for two policies that provide the same environmental result (piezometric level).

6.4.2 Economic model

The economic model represents the behaviour of the farming sector at the beginning of the agricultural season with regard to yearly crop and input (land and water) allocation to available agricultural land. The economic model is specified at hydrogeologically uniform regions (see 6.4.3). Essentially, the main difference with the economic objective in Chapter 5 is that the model will be run each year and, as a consequence, has to represent the yearly adaptation of farming. It means that short term equilibrium has to be modeled as opposed to long or medium term equilibrium. However, Positive Mathematical Programming (PMP) models that allow for intensive adjustments (adaptation of the water application per hectare) such as those developped in Chapter 5 are well adapted to do so. In the short term, intensive adjustments are very likely to occure, because they imply no structural change, and rather just an adaptation of the input application level. As such they seem very important to be integrated as a possibility in such economic models. Conversely, linear programming models would be less suited because of their *jumpy behaviour* characteristic and their nearly purely financial response[8]. Indeed they do not account for none observed (typically non marketed) costs or benefits that are enabled by non-linear forms such as PMP models.

The economic farming model adopted here is similar to that developed in Chapter 5. It is a regional programming model of agricultural supply based on the principles of PMP (Howitt, 1995a) with decreasing marginal yields at the crop level and constant elasticity of substitution between land and water for irrigated crops as refined by Mérel et al. (2011) ($\sigma = 0.15$ here). It is calibrated with the so-called profit rule which means that the observed reference and the accounting profits are perfectly replicated. The two other rules could have been also implemented, but we believe the profit calibration rule to be more likely to be accepted by decision makers as they might be interested in the evolution and replication of profits. The main difference with the profit model of Chapter 5 is the specification of the water cost function which we specify as a function of the aquifer depth (recall it was fixed in Chapter 5).

The per cubic meter water cost (c_{i2}) is stock-dependent and is a function of the piezometric level of the aquifer (h_n), the remaining parameter are fixed and their values are given in Appendix. The linear function is as follows:

$$c_{i2} = r_{ae} + c_{energy} * \frac{g * l(h_n)}{\eta_{pump}}$$

with r_{ae} the water agency tax, c_{energy} the unit energy cost (electricity here), g the acceleration of gravity, $l(h_n)$ the total head loss, and η_{pump} the efficiency of the pump.

Another particularity is that we specify a constraint that avoids applying too much water on crops (the upper bound is defined as 1.5 times the reference dry water application per hectare and crop) in the case of a simulation with no more regulation, that is a far from the reference calibrated situation. This is necessary because of the specification of the model (see discussion in Chapter 1).

In simulation, the economic model runs each year with the available water (b_2) and water costs (c_{i2}) calculated according the piezometric head h_n of the given year. We assume that farmers make their cropping pattern and water application decisions for a relative dry year

[8] As already discussed in Chapter 1 the behaviour of linear programming models that maximize profits favour the highest gross margin activities and have difficulties to represent the observed input allocation and cropping patterns

(Bouarfa et al., 2011). This could be justified by a risk averse behaviour.[9] The optimized cropping pattern is supposed to be realized, but the real water application is actualized according to the weather conditions that occur in late spring and in summer.

6.4.3 Hydrogeologic model

One of the issue raised here is that the hydrological model is often very simplified in integrated hydro-economic modeling (see e.g. Knapp et al. (2003); Esteban and Albiac (2011)). One of the objectives of this work is to develop a fitted hydrogeological module that replicates correctly past trends and is calibrated both on the hydrogeological phenomena.

The hydrogeological model set-up followed three main steps. The first aimed at defining homogenous hydrogeological zones, the second focused on gathering the data and calculating some model parameters, the third step concentrated on the model refinement and calibration.

As discussed in Chapter 1 the Beauce agricultural region is divided in 4 regulatory zones. However, to better represent the hydrogeological processes, we disaggregated the Beauce into six homogeneous hydrogeological zones. This zoning is based on geological characteristics and on relatively homogenous infiltrations. It is still coherent with the regulatory zoning: The Beauce Centrale is redivided into three zones and the three remaining zones are kept as in the regulatory zoning. See Figure 6.1 for this new zoning.

The hydrogeological model has been refined from the simple groundwater mass-balance equation that states that the piezometric level at the beginning of the growing year, h_{n+1}, is a function of effective natural recharge (R_n), natural drainage (D_n), withdrawal per year ($W_{t,n}$) and per sector t (agriculture, drinking water, industry) , storage coefficient (C_{en}) and area (S). The natural drainage is understood as the natural flows to other systems (other aquifer or surface flows). In the Beauce case, the drainage towards surface river systems is significant. We characterize the drainage in year n as the sum of the drainage of year $n-1$ and a term that is proportionate to the head difference between two years $h_n - h_{n-1}$. The effective recharge, R_n, is the volume of water which reaches the aquifer in year n from the surface (rain, surface waters). Because of the inertia in the system, which is characteristic to the Beauce aquifer system, it is composed of the infiltration, I_n, directly dependent from the yearly precipitations, but also from the previous year infiltration. The important aquifer

[9] However, note that the economic model does not account for risk. This is partly justified because it is a regional model.

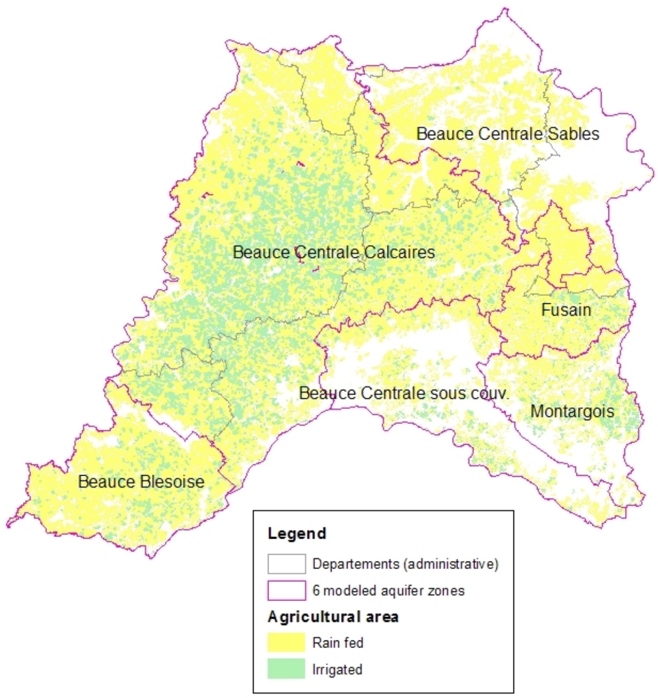


Figure 6.1: Zoning adopted in the hydro-economic model

size and thickness characterize the inertia of the system and its long reaction time. Periods of drought, for example, will not cause sudden lower groundwater levels, but the effect will be buffered over several years.

We assume that the conductivity within each zone is such that the level of the aquifer on the 1$^{\text{st}}$ of April of year n is homogeneous over each zone and represents the sum of extractions of year $n-1$.[10]

Our model is as follows (aquifer regional index is omitted for clarity):

$$h_{n+1} = h_n + \frac{R_n - \sum_t [(1-\beta_t) * W_{t,n}] - D_n}{S * C_{en}}$$

with

$$\begin{cases} D_n = D_{n-1} + c_d * S * (h_n - h_{n-1}) \\ \\ R_n = (I_n + c_r * I_{n-1})/(1 + c_r) \end{cases}$$

β_t is the return flow from the extraction back to the aquifer. Note the drainage coefficient c_d represents the share of the drainage that is due to the head pressure implied by the difference of the head in year n and year $n-1$. c_r is an inertia term that applies to the recharge of year $n-1$.

6.5 Data and calibration

Data that are specific to the economic model are the same as in Chapter 5. As the zoning is different, the regional aggregation of observed cropping pattern is renewed to fit to the six regions defined in this Chapter with the help of GIS (Geographical Information System) intersections. The total area modeled remains the same (582,500 hectares). Note that, except the cost of water which is recalculated every year according to the piezometric head, all others economic parameters and mainly the product and input prices are not varied with time. Even if this is not really realistic it enables to assess the marginal effect of the regulation system on the state of the groundwater resource.

Figure 6.2 shows the different calibration years for each of the sub-models.

[10] see Pfeiffer and Lin (2012) for a critical discussion on this assumption.

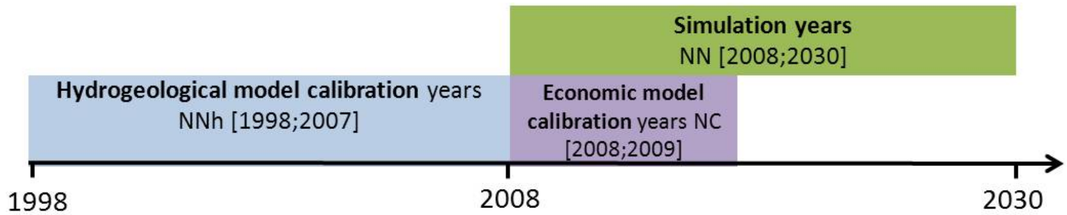


Figure 6.2: Calibration years for each of the sub-models

6.5.1 Hydrogeological model calibration

Piezometric heads, withdrawals and recharge are observed for the calibration period. The calibration phase aims at calibrating the following model parameters: storage coefficient C_{en}, the drainage coefficient c_d and the recharge coefficient c_r which are independant from years. It will also serve to initialize the value of the drainage which is unknown.

Data used for calibration of the hydrogeological model are of three types:

- **Piezometric heads**. Groundwater monitoring data for the reference piezometers of each of the hydrogeological sectors are collected from the national data base for groundwater (ADES ; www.ades.eaufrance.fr). We assume that the piezometric heads of the reference piezometers are representative of each zone. They have been chosen as "reference piezometers" by the administration in order to follow the state of the groundwater and impose groundwater withdrawals restrictions to the corresponding areas in accordance with the piezometric head (Verley, 2003).

- **Withdrawals**. A water withdrawal database has been set up from data produced by water agencies upon taxes recovered for water uses for the years 1998 to 2009. This database enables to compile water withdrawal per type of user (water utilities for drinking water distribution, industries and farming), per area, per type of resource and per year. It should enable to have a good approximation of the total water that is withdrawed from the aquifer as farmers have to declare their withdrawals and pay the according tax. However, there is a minimum volume (7 000 m3) under which farmers have not to declare their water use.[11] We assume that the very large majority of withdrawals are submitted to the payment of the tax, and, are as such in the database. In order to correct the data we added 10% of

[11]Note that this volume correspond to less than about 4 hectares of irrigated corn, or about 10 hectares of irrigated wheat

the observed agricultural use volume to account for missing data. For water utilities and industry we assume that all volumes are declared and in the database we use.

-**Infiltration**. Infiltration are calculated for each year and aquifer zone. The limestone aquifer is characterized by high infiltration rates, but sandstones and clays show more surface runoff. The recharge is calculated from two values: the effective rainfall and a geomorphological index. This index (called IDPR) represents the characteristic of a soil with respect to infiltration and runoff. The estimation of this index is detailed in Schomburgk et al. (2012). It correspond to the percentage of water that infiltrates. Effective rainfall is the rainfall that is available for runoff or infiltration. It is calculated from meteorological data (MeteoFrance) available at a grid size of 8 km*8 km.

β_t are set to zero in the case of the Beauce aquifer because no return flows to groundwater are considered significant from irrigation or sewage.

The hydrogeological calibration programme consists in minimizing the distance between each year and each zones' estimated piezometric level h_n as specified in our model and the observed piezometric level using non-linear least squares. The dynamic program is solved in GAMS with a non-linear solver. Calibrated parameters values are given in Appendix Table 6.1.

The following table gives the parameter values and support values for the hydrogeological model.

	B. Bles.	B. c. calc.	B. c. sables	B. ss couv.	Fusain	Montargois
Area (km2)	982	4616	1684	1224	469	777
c_{en}	0.054	0.070	0.058	0.027	0.067	0.086
c_d	0.131	0.216	0.230	0.111	0.329	0.588
c_r	0	0.308	0.474	0.394	0.097	0.053

Table 6.1: Parameter values for the hydrogeological model. c_{en} is the storage coefficient, c_d the drainage coefficient, c_r the recharge coefficient.

The calibration performs well as the observed and modeled piezometric levels for all regions are close (see the Appendix 6.8 for the Figures that compares observed and modeled years). The Nash-Sutcliff index (Nash and Sutcliffe, 1970) is 0.969, 0.995, 0.986, 0.977, 0.962, 0.949 respectively for the 6 regions and 0.978 for the whole model. (A perfect fitted calibration would give an index of 1).

6.6 Design of alternative management scenarios

We define 4 alternative management scenarios and two extreme scenarios that serve mainly to assess the interval in which the system can be. The two extreme scenarios are the following:

- The open access case

In this scenario we tested the impact of a scenario with no regulation, in other words where the actual quota scheme is abandoned and where groundwater becomes an open-access resource. This scenario enables to explore the trade-offs between the welfare gain of farming and the decrease of piezometric levels.

- Stop of irrigation

This scenario is only simulated with the hydrogeological model (it would be too far from the reference to be used with confidence with the economic model which would be constrained to set all irrigated areas to zero). It enables to see the impact of irrigation on the aquifer and what would be the maximum possible level to reach by reducing agricultural demand and withdrawal (drinking water and industry demand remaining).

Alternative management principles are as follows:

- Baseline with 6 different regions

In continuity with the zoning of the hydrogeological model based on hydrodynamic properties of the underlying aquifer zones, we tested the baseline scenario but by differentiating the Beauce Centrale in three sub-areas to explore whether diciffering the coefficient and corresponding water withdrawal rights would enable to improve the level of piezometric heads and at what cost for farming.

- Allowing transfers

As in Chapter 5 we tested the impact of removing the water constraint at the regional level allowing for potential water transfers across regions. In concrete they could be realized through water right exchanges or trading between regions. This option enable to simulate the opportunity of a market.

- Lag in calculation of water right coefficient

As the aquifer presents a certain inertia it could be envisionned to introduce this characteristic in the regulation. We designed a new way to calculate the yearly coefficient by specifying that it depends on the average between h_n, h_{n-1} and h_{n-2} instead of h_n only.

- Water fee based on the piezometric level

We tested a price based instrument that gives a signal to the water user on the state of the water resource. Several instruments could be tested. We designed a water fee that is as follows $r_{ae} = r_{ae-ref} * (1 + h_{highRef} - \tilde{h}_n)$, with $\tilde{h_n} = \frac{h_n + h_{n-1} + h_{n-2}}{3}$. It means that the current level of the tax would be multiplied by the difference between a mean observed piezometric level and a high water reference piezometer level (2001 is taken as a *high water* reference). If the water level is x meter below the reference level, the tax would be increased of respectively $x * 100\%$. This can amount to significant tax increases. Note however that the reference tax level is 0.014 €/m^3 and that the shadow value of water is zero in Beauce central sable and that among the other regions the lowest shadow value of water is 0.03 €/m^3 in the reference situation. This tax can be charaterized as an ambiant tax (Segerson, 1988) as all farmers located on the same aquifer area will face the same tax, whatever their individual behaviour of water use is. It is the collective total water use that impacts the level of the aquifer.

- Groundwater resource substitution

One of the debated options envisioned by the administration is to allow for the development of substitution water resources to compensate the reduction in water availability in the eastern part of the region, say in Montargois and Fusain. The substitution resource would be water collected over the wet season in artificial ponds. Note that we assume that this would not affect the infiltration in the aquifer. The investment costs are estimated to be around 5 € per cubic meter. With a 30 year discounting, the per cubic meter costs amounts to 0.29 € per cubic meter.

6.6.1 Simulation of future climate scenarios

To simulate the evolution of the hydro-economic system in the future with Monte Carlo simulations and thus integrate uncertainty on climatic variables, provision of climatic scenarios are required. We developed a simplified approach to produce these scenarios as the application of downscaling methods were beyond the scope of this research. Boe et al. (2009) details the various methods available to produce climatic scenarios and propose an application to French river basins. For each Monte Carlo simulation a series of climatic years are randomly drawn from past years for which data were available (i.e. 1970-2007) to simulate the years 2013- 2040.[12] A climatic year is characterized by regional infiltration and efficient precipitation. These climatic variables are than transformed as follows. For each Monte Carlo simulation a random "climate change" coefficient is drawn between 0 and -30%. Boe et al. (2009) give a decrease of about -3% for spring and -10% for summer precipitation in the Loire river basin and +19% evapotranspiration in spring and -13% in summer -both parameter intervene in the infiltration determination- ; they provide similar patterns for the Seine river basin. However, their estimation are for the period 2046-2065. This "climate change coefficient" is multiplied by the infiltration and efficient precipitation. The Monte Carlo simulations are repeated 200 times to provide 200 climatic scenarios that account for a reduction in infiltration and efficient precipitation with effects on groundwater balances and crop water needs.

6.7 Simulation results

6.7.1 The baseline

The baseline scenario corresponds to the reference (2008/2009) groundwater management rules based on yearly revised water quotas according the yearly coefficient (a function of the piezometric level in each of the four regulatory zones).

We simulated the effect of the baseline scenario up to 2040 on the hydro-economic system with Monte Carlo simulation and using the climatic scenarios produced as detailed in the precedent paragraph.

The following Figure 6.3 shows the evolution of the average (of the 200 Monte Carlo scenarios) piezometric heads for the six regions and the associate total withdrawal by farming. In the medium term the system seems to be efficient with regard to the maintaining of the piezometric levels. Implied water coefficient are different according regions and this justifies the choice of the administration to distinguish the four zones.

[12] A first test was realized to see if the distribution of past years was statistically similar to a normal law or other common probability laws, but this was not the case. This would have enabled to produce more consistent future climate scenarios that would not replicate exactly the distribution of past years and that could have been modified on their standard deviation also. A longer time period would have probably enabled to fit a probability law.

Interestingly, the baseline scenario will induce, on average, lower piezometric levels than past years (1995-2008) for some aquifer regions and similar ones for others, suggesting different sensitivities of the agriculture-aquifer system areas to climatic change (i.e. an increase of about 15% in infiltrations). This can be observed by comparing the light dotted lines (1995-2009 average piezometric levels) with the full lines (baseline scenario >2010). Beauce centrale calcaire, Beauce sous couverture and Beauce Blésoise seem to be sensitive to climatic change. However, this statement should be confirmed with a marginal analysis, fixing agricultural water withdrawal and concluding on the resource sensitivity.

However the analysis of the differences between scenarios shows that the system is very much influenced by the precipitations: see Appendix 6.9 were several random scenarios effects on the piezometric levels are given (similar patterns exist for the other regions).

Our results would not call for a specific strengthening of the constraints (i.e. reduction of the coefficients) in the eastern part of the territory (Montargois and Fusain) as discussed within the SAGE, unless if these levels are not satisfactory from an ecological point of view and are not sufficient to feed the natural surface water ecosystems.

Another recent evolution, in the water governance (adopted march 2012) was to limit the regional differences between the coefficients to maximum 10% between Montargois and Fusain with respect to the Beauce centrale. This was decided for the sake of equity between farmers in Beauce. Our results suggest that for the baseline scenario the coefficient are, on average (between 2010 and 2040), 39% less in Montargois and 26% less in Fusain than they are in the Beauce centrale. This would suggest that this option would relax some of the constraints in Fusain and Montargois at the cost of a decrease in piezometric levels.

	B. Bles.	B. c. calc.	B. c. sab.	B. ss couv.	Fusain	Montargois
Shadow value	0.144	0.040	0.006	0.120	0.071	0.130

Table 6.2: Shadow values of water (€/m^3) over the values for the simulated years 2010-2040.)

6.7.2 Open access case

The open access scenario is also simulated with Monte Carlo simulations. On average over all 200 climatic scenarios, the open access case results in a decrease of piezometric levels for the majority of regions, Beauce sable is the only region which seems not to be affected by an open access to its groundwater (see Figure 6.3). A reason is that the shadow value

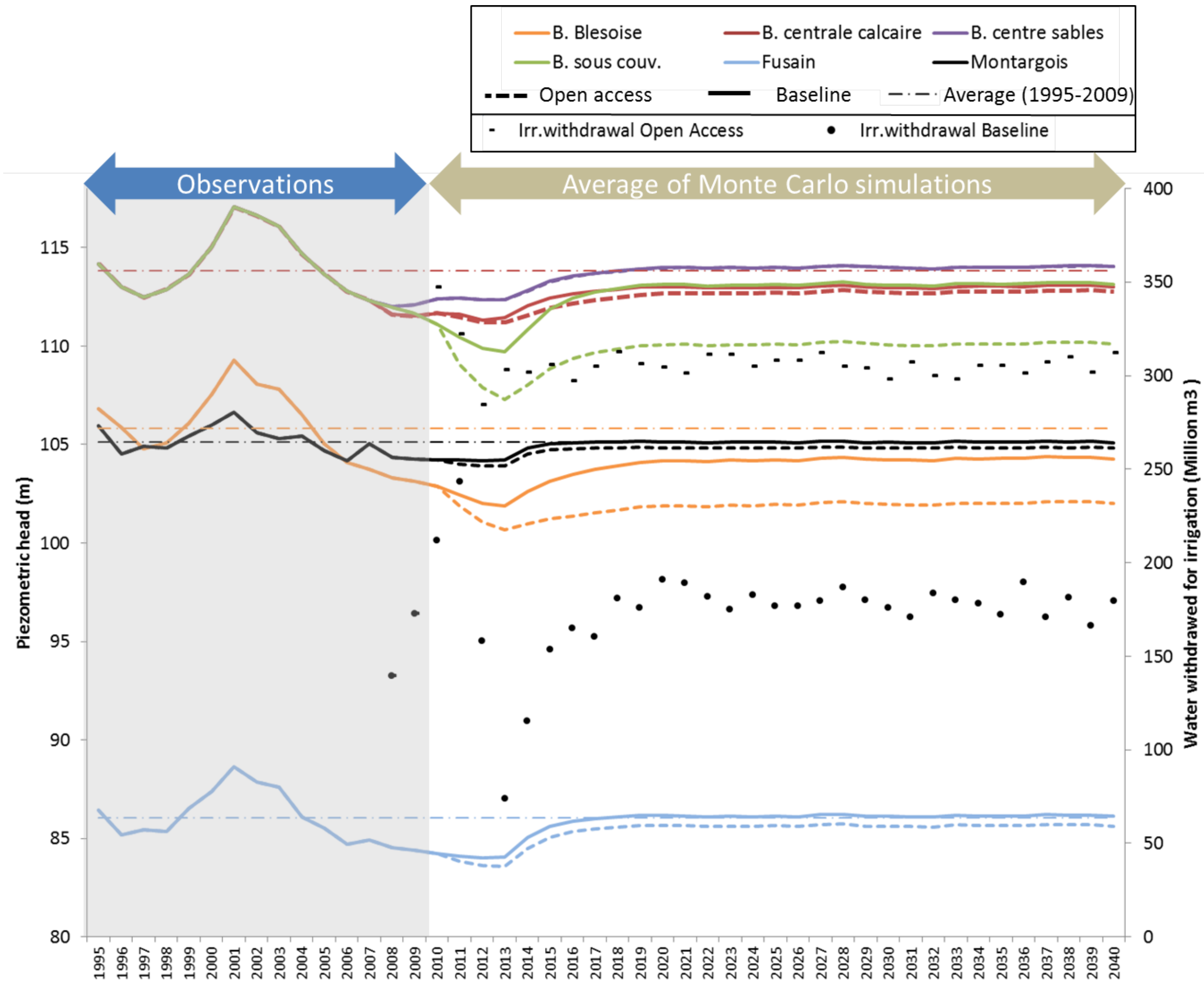


Figure 6.3: Evolution of the average piezometric head (meter) and irrigation withdrawals for the baseline scenario and the open access case up to 2040 (average of the 200 Monte Carlo simulations)

of water (i.e. benefit of having an extra cubic meter to irrigate) is very small 0.6 € cents, and that the water demand by farming would not increase a lot.

The reduction of the aquifer level is very significant for the Beauce Blésoise and the Beauce sous couverture.

However, the diversity of levels is important according years and scenarios according precipitation and infiltration as discussed in the baseline case.

The fact that the open access case turns out to have lower groundwater levels, shows that the cost of water is not a major i.e. sufficient incentive for the farmers to limit their abstraction so that the piezometric levels are not affected, at least at the regional level. The Gisser-Sanchez effect can not be validated on our case study as self regulation does not take place at a sufficient level to maintain the levels.

The following Table 6.3 gives the average (for the 200 simulations) water withdrawal from the Beauce aquifer for each of the four regions in the open access case compared to the baseline. The irrigation withdrawal volumes are also shown on Figure 6.3. They are significantly different, on average, for both the baseline and the open access case. These numbers partially explain the differences in piezometric level observed on Figure 6.3 ; note that Beauce centrale sable shows small differences between both cases, indicating also that water is not very scarce for farming in this region (low shadow values in the baseline see also Table 6.2).[13]

	B. Bles.	B. c. calc.	B. c. sab.	B. ss couv.	Fusain	Montarg.	Total
Open access	35.3	178. 6	4.4	47.4	14.4	16.4	296.5
Baseline	9.9	152.0	4.2	11.7	7.6	4.9	190.3
Share B/AO	28%	85%	96%	25%	53%	30%	64%

Table 6.3: Average water withdrawal from the aquifer (Millions m^3/year) for the simulated years 2010-2040 for the Open access case (OA) and the baseline (B) and the share of water withdrawed in the baseline case on the open access case

Figure 6.4 gives the distribution of the piezometric levels for the Beauce Blesoise and illustrates the stochastic dominance of the baseline case over the open access case.

The open-access scenario induces an average gain of 5 Millions € per year or, in average, or +1.5% compared to the reference situation, which is a relative small gain. The average

[13]shadow values for water equal zero in the open access case because water is available without constraints at the pumping cost.

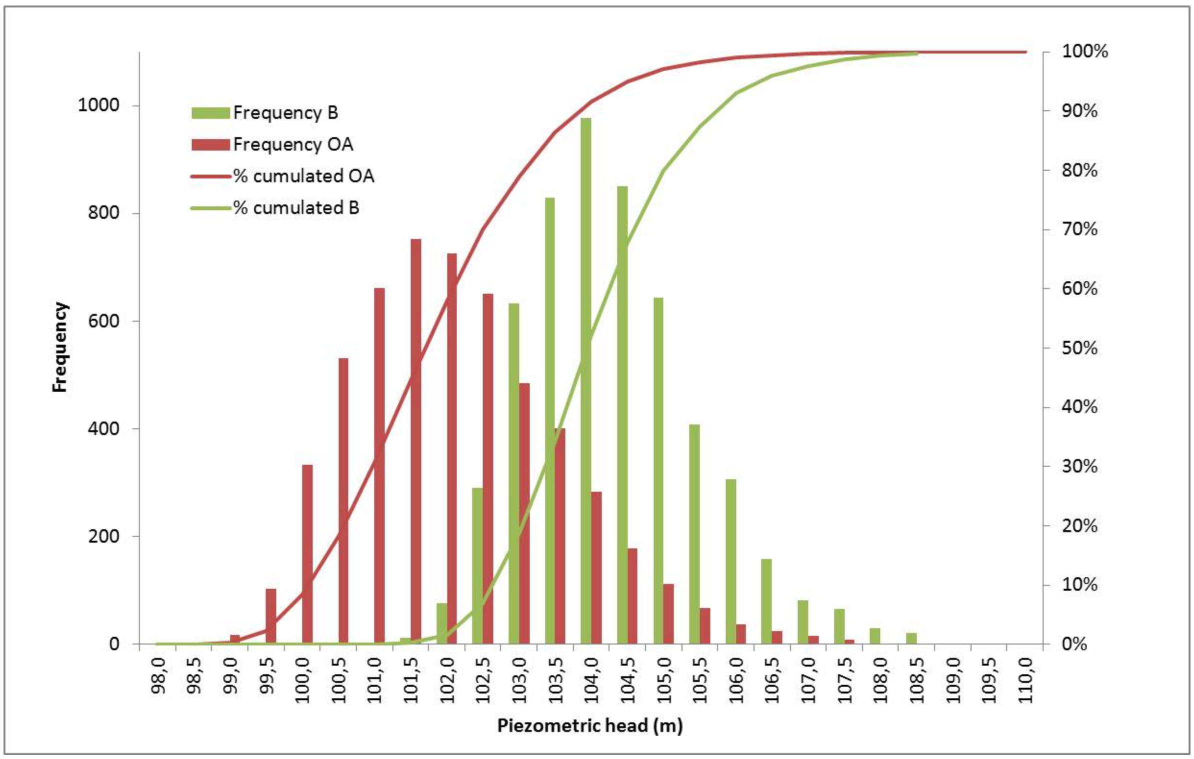


Figure 6.4: Distribution and density of the piezometric head (meter) for the Monte Carlo simulation and all years in the open access case and the baseline case for the Beauce Blesoise region. OA stands for Open-Access and B for Baseline

benefit (extra-profit compared to the baseline) from open access case can be estimated with the simulation results to 0.060 € per extra m^3 withdrawed. In another word, the quota system (here the baseline) do not seem to have constrained farming to much. However, farms that are specialized on affected crops might be affected significantly as well as the transformation industry (Lejars et al., 2012).

Cropping patterns have been modified compared to the baseline. They are little variable according years. The main change is the increase in average irrigated corn areas (about +88%) and the reduction in areas grown with rain fed corn (about -44%) and sunflower (about -20%). Irrigated sugarbeets also increase (about +14%). The difference between climatic scenarios are low as the land grown per crop are always in a range of +- 7% of the average (on average in a range of +-1.9%) . Most variability is observed for irrigated and rain fed corn.

In the open access case water intensity application rates vary on average from 0 to +55% depending on crops and regions compared to the baseline. Corn water application rates vary from 0 (in Beauce sable) to +27% (in Montargois). Higher water application intensity increases are observed for wheat and barley. Water application level show modest variability with years and scenarios.

6.7.3 Comparing alternative management scenarios

In the remaining of the result section we analyze the results for a unique climate scenario only, because the focus is the comparision between scenarios.

The following Figures 6.5 and 6.6 compare the results of the piezometric level for three different regions. The three other regions show very small differences for the majority of scenarios. As illustrated with the black rounds on Figure 6.6, the different instruments can not be ranked from the more effective to the less effective in a unique order and according years (i.e. precipitation conditions) their order is changed. Interestinly, the results indicate that the baseline scenario is the less costly of all tested scenarios (except the transfer option that will be discussed later on), which encourages to maintain the actual management scheme.

The option "Baseline with 6 regions" that consists in introducing a differentiation between the three regions: Beauce centrale, Beauce sables and Beauce sous couverture seems relevant in the calculation of the yearly coefficient for Beauce centrale and Beauce sous couverture, but the differences with the baseline are very small and only notable for some years. From a cost-effectiveness point of view this option nearly changes nothing (+ 1.5 and + 1.3 €/ha/m head for the Beauce calcaire and sous couverture respectively).

Integrating inertia in the calculation of the coefficient, i.e. adding the two last years piezometric heads to the present year head in the coefficient calculation (lag alternative) seems not to be relevant. When infiltration (precipitation) are on a decreasing trend, then the lag instruments "recalls" the better years and indicates an overly optimistic signal to the farmers that can withdraw more water than in the baseline equivalent year, turning out in lower piezometric levels when they are already low in the baseline. Conversely, when infiltration are on an increasing trend, the lag coefficient "recalls" the worse years and indicates to the farmer to withdraw less, turning out in higher piezometric levels when they are already satisfactory in the baseline. The cost of this option is similar to the baseline, but is less satisfactory in terms of piezometric levels.

The price based instrument consists in varying the level of the water agency fee according the difference between a reference *high* piezometric level and the yearly level. It has the aim to indicate, through a price signal, the relative scarcity of the resource. This incentive instrument seems very efficient to reach higher levels than the baseline in the Beauce centrale. For the remaining regions the difference with the other instruments are small and might not justify the extra cost. Indeed, the cost-effectiveness ratio is the highest for this instrument (33 €/ha/m head and 20 € higher than the baseline).

The transfert option appears to be the less costly to Beauces agriculture as a whole, but has very different impacts on groundwater according regions that would import or export water. The results state that the exporting regions are the Beauce centrale and the Beauce sable. They export about 30% of their own water use for irrigation. However, these exports are variable according years and vary from 7 to 82% of the water use for Beauce centrale and from 0 to 191% for Beauce sable which exports no water two out of three years. The importing regions are all other four, but Fusain is a small importer (on average 7% of its water use and 3 years over 30 it is even a very small exporter). Even if the transfert instrument seems appropriate in the Beauce centrale calcaire, it has a negative impact on groundwater levels in regions that are net exporters: in Beauce sous converture this scenario is even worse than the open access case. As such the transfer scenario seems not to be relevant at least without any extra control of the groundwater resources effect.

The groundwater substitution option consists in allowing Fusain and Montargois farmers' to substitute some of their groundwater withdrawals for irrigation with water collected in ponds over autumn and winter. The simulation suggest that only very limited water

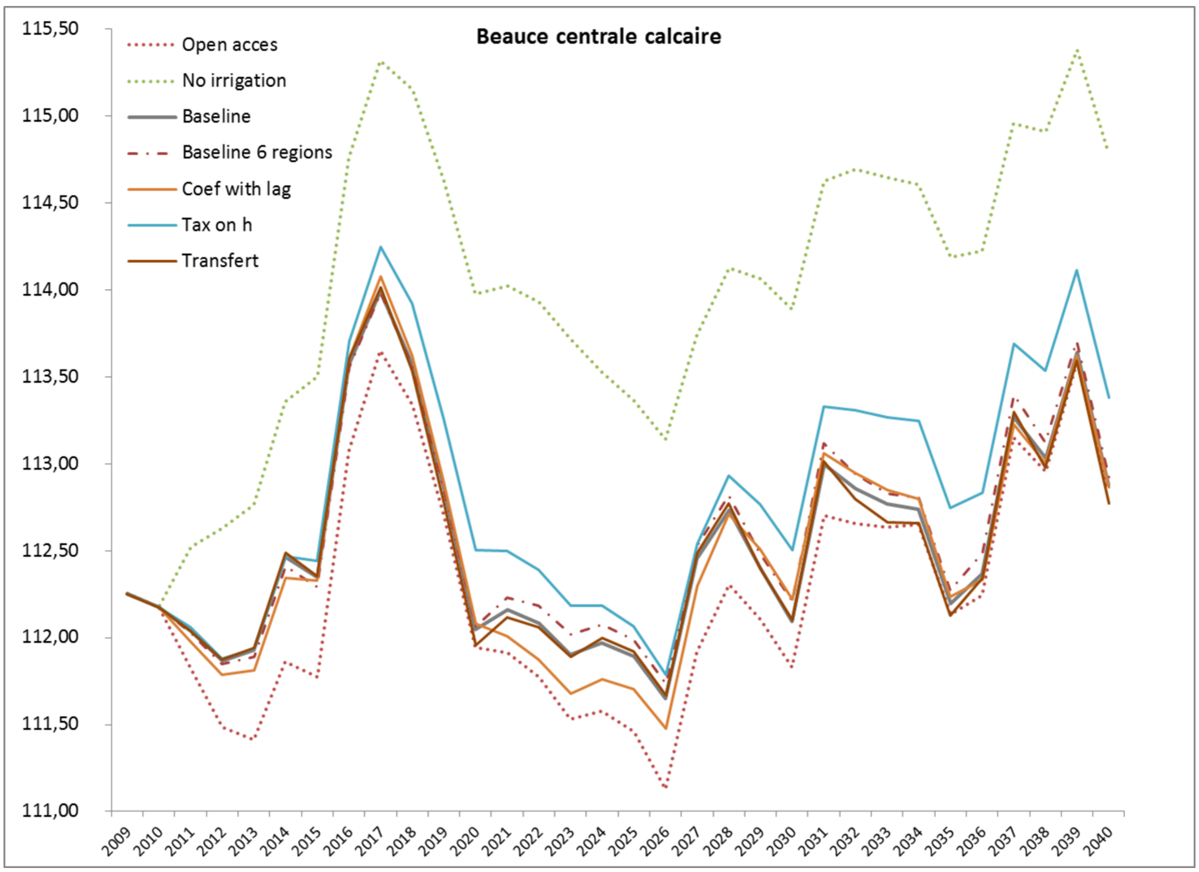


Figure 6.5: Evolution of the piezometric head (meter) in the different scenarios for the Beauce calcaire centrale (largest region) given climatic scenario

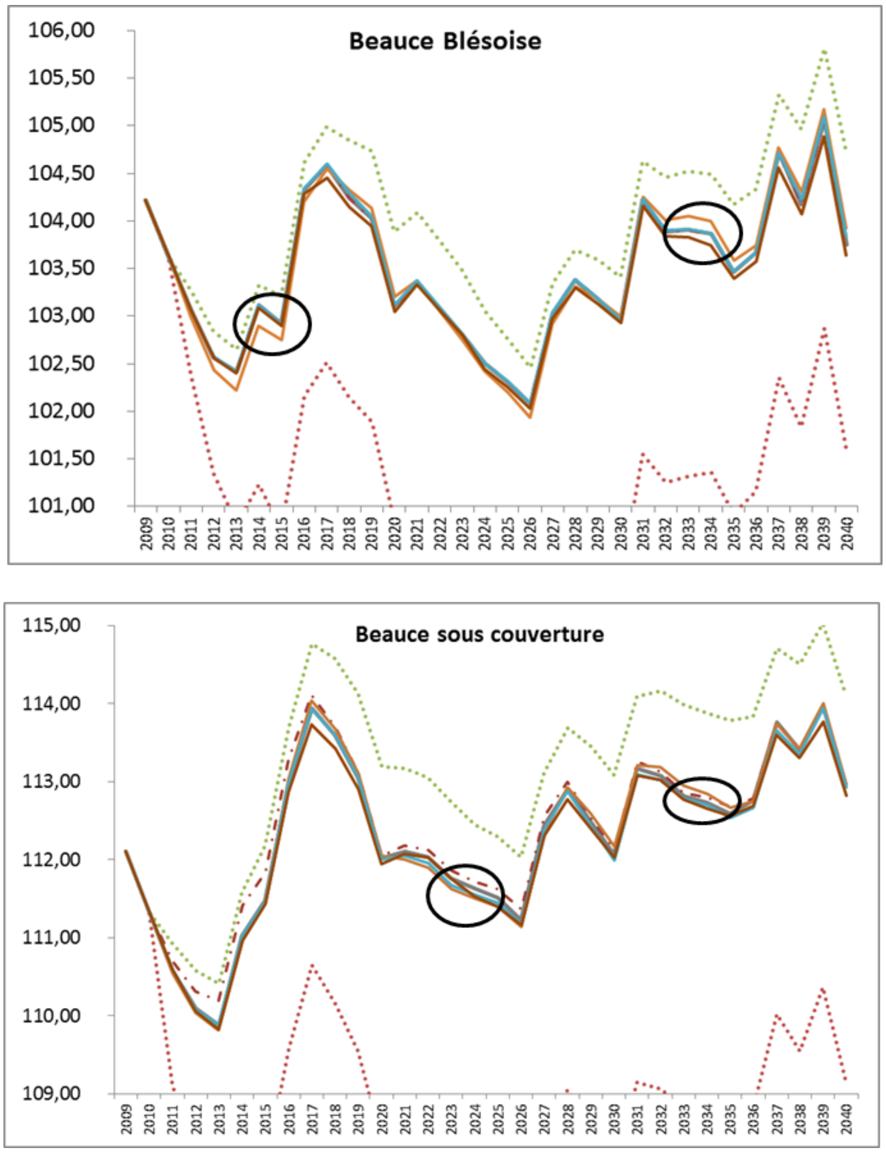


Figure 6.6: Evolution of the piezometric head (meter) in the different scenarios for the Beauce Blésoise and the Beauce sous couverture given climatic scenario

will be collected and used for irrigation: in Fusain between 7 and 12% of the amount of water withdrawed from groundwater is used from ponds and in Montargois only 1 to 3%. According years, the pond water is used in substitution or in complement to groundwater. This option does not seem to be a significant solution in the medium term, because the cost of the substitution is not significantly lower than the cost of groundwater and the cost of the shadow value of water for irrigation (i.e. the opportunity cost of extra water use). The per cubic cost of a substitution resource should be significantly lower than the groundwater cost for farmers to be substituted or lower than the shadow value of water to increase the overall use of water. If the constraints on water resource availability would increase, this substitution water could start to be used at a more important level and this solution developed by farmers.[14]

The following table gives the cost-effectiveness ratio for the different scenarios.

	All	B. Bles.	B. c. calc.	B. c. sab.	B. ss couv.	Fusain	Montarg
Baseline	10,9	7,4	3,6	0,3	15,2	4,1	79,7
Baseline 6 reg.	11,8		5,1	0	16,5		
Coef with lag	11,0	6,6	3,2	0	15,3	4,2	84,1
Tax on h_n	33,1	10,6	35,3	31,6	20,6	8,9	85,9
Transfert	22,0	3,2	37,2	4,2	5,2	3,1	32,0
Substitution	10,7					2,4	77,3

Table 6.4: Cost-effectiveness ratio for the different scenarios and regions in € per agricultural hectare piezometric meter increase per year (average). No numbers are given when they are similar to the baseline

6.7.4 Discussion on the pumping externality

As the irrigation water is abstracted from the groundwater, the farmers face a cost that is a function from the head levels as shown by the definition of the cost of water in paragraph 6.4.2. In this context, auto-regulation or an internalisation of the pumping externality might occure due to the increase in water cost following an increase in the depth of the water table faced by the farmer. Interestingly we found that the pumping externality effect (dc_{i2}/dh_n) on water costs is nearly absent and it does not influence the behaviour of farming. The

[14]The shadow values indicate that the region that best values water (i.e. where the shadow values are higher) is the Montargois region, in the eastern part of the area, where substitution resources are envisioned and debated by the administration and farmers. Note however that the shadow values of water on which the model have been calibrated are taken from the first PMP stage and this procedure can be discussed (see Chapter 5).

piezometric level decrease by -0.03% on average if we compare the results from our model that accounts for the pumping externality by integrating a piezometric dependant water cost function and a model in which the cost is not anymore dependant from h_n but only on h_{2008} (i.e. reference level).

We estimate the increase in water cost to 1 € per 1000 cubic meter for one meter increase in piezometric level depth. This is not sufficiently important to internalize the problem of resource depletion as we can see that piezometer levels decrease in the long term. For a 1 meter decrease in piezometer level, the water cost per hectare corn would increase of 2 €. The total cost of water is 55€ per 1000 cubic meter in the reference situation i.e. about 100 € for an hectare of corn and the increase in cost would be of 2 € with a 1 meter decrease, whereas the shadow value of water is above for 4 of the 6 zones (see 6.2).

Even if the experiment proposed here is not exactly the same as the classical "Gisser-Sanchez" problem (Gisser and Sãnchez, 1980) which compares no regulation (called competition) with optimal control (i.e. optimisation over a discounted flow of future profits), we can discuss the results presented here at the light of this litterature. The difference is that our regulated case does not correspond to optimal control but to a regulators' norm -water withdrawal maximum- that has the aim to ensure an ecological objective. In an other word its aim is to maintain the piezometric levels above some critical thresholds to ensure surface water systems have sufficient flow that in turn ensures good ecological state.

If we assimilate our control case to Gissers' optimal control case, our case study does not validate the Gisser-Sanchez effect that states that regulation is not worth compared to no regulation of groudwater.[15] This result might be explained by the hydrogeological model specification which is more detailed than a simple bathtube model used in Gisser and Sãnchez (1980) (our recharge is not a constant and depends from previous years), and also because the storage coefficient is not very large in Beauce. Note that the specification of cost of water are linear in their model as in ours.

6.8 Conclusion

The hydro-economic model developed is an interesting approach to explore a variety of management alternatives and policies on the hydrogeologic and agricultural economic system. The interest of the proposed approach is that it suits all types of policy exercises and

[15] No regulation is even better, because the transaction costs of a regulated governance are absent.

gives detailed insights into the agricultural economics: for instance shadow values of water enable to interpret the behaviour of farming with respect to alternative water resources. We believe our model to be a good trade-off between detailed modeling and calibration on one side, and implementation and data requirement on the other side. Our hydrogeological modeling approach, although relatively simple (not a distributed model) performs well and enables a large variety of application. We found the approach to be satisfying from a calibration point of view, because it replicated correctly the observed years. As such it is promising in terms of applications in interaction with local decision makers. The main advantage is to have a unique platform that both accommodates a variety of simulations and that is accurately hydrogeological and economically calibrated. However, one of the limitations that we discuss in detail in the Synthesis Chapter is that the "No Regulation" case might be too far from the reference to be modeled with confidence with the economic model used.

The simulations enable to draw some interesting results. Among other we show that the tax instrument seems more effective than the current management scheme (higher piezometric levels) eventhough it induces more costs on the farming sector. Introducing a lag in the calculation of the coefficient does not seem relevant, because it makes the coefficient not "reactive" enough when levels are decreasing. The transfert option does not seem to be appropriate, because it causes some piezometric decreases in exporting regions, although it is interesting from a pure agricultures' economic point of view (see results in Chapter 5). This result enlightens the interest of a hydrogeological representation of each of the aquifer zones. We also show that for the Beauce aquifer system the pumping externality has a negligible effect on pumping cost, and water cost are far from the marginal benefit of irrigation in order to have a significant impact on water demand. This is an interesting finding as this latter link is often considered as a central assumption in several analytical models of groundwater use, and this is one of the reasons that explain the Gisser-Sanchez effect.

The purpose of such a model after detailed validation is to assist the reflexion of a stakeholder group to envision and evaluate several alternatives to manage groundwater at least cost for the farming sector. This model could be further developed to suit stakeholder knowledge and requirements. Particularly, it could be worth to think about alternative indicators (such as the cost-effectiveness ratio here) that are meaningful to stakeholders and enable to synthesize the results in few indicators only.

There are other perspective of this work. A first option would be to explore the capacities of the model to realize joint optimization in both the economic model and hydrogeological model. This would consist in specifying an objective in the piezometric levels (for instance no decrease in the levels) and see the implication in terms of economics. Then it might be possible to derive the best adapted instrument.

A sensitivity analysis could be realized on several model parameters of the hydrogeological and economic model to test overall model reliability. A better representation of the other water demands, (i.e. drinking water and industry by integrating water demand functions for these sectors instead of fixed water demands) would enable to better represent these demands and to explore the likely effects of a water market between sectors. An interesting perspective would be to look at the impact of the evolution of price expectancy, as we do in Chapter 4, on the piezometric head and its relative effect compared to water policies. Last the opportunity to integrate interannual time periods to represent the inter annual variability (e.g. precipitation) could also be envisioned so as to improve the representation of the system and evaluate the interest of more time-disaggregated policies (rights/coefficient that evolve within the year according the state of the groundwater).

Appendix to the data

In the application following values are taken: $c_{energy} = 0.07$ €/kwh
$\eta_{pump} = 0.70$
$r_{ae} = 0.014$ €/m3
Total head loss : $l(h_n) = 150 - h(n) + 6$
$150m$ being the soil level above sea level and $h(n)$ the height of the aquifer. 6 is the estimated head loss in the pumping configuration.

Comparision between observed and modeled piezometric levels for the six hydrogeological aquifer regions

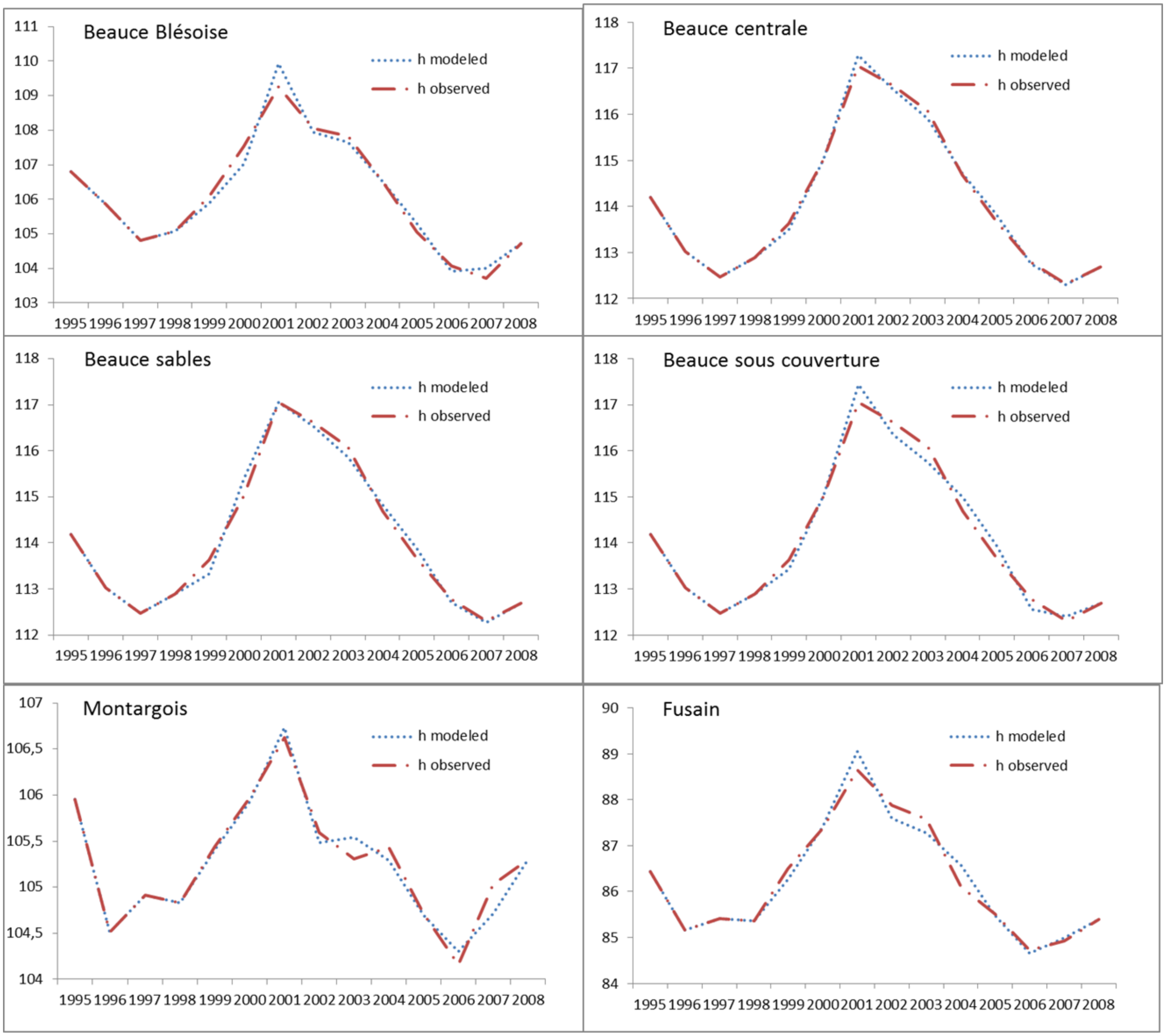


Figure 6.7: Comparision between observed and calibrated model results for the hydrogeological model for Beauce Blesoise and Beauce centrale calcaire

An example of relationship between piezometric head and calculation of the coefficient for the Beauce centrale (largest region)

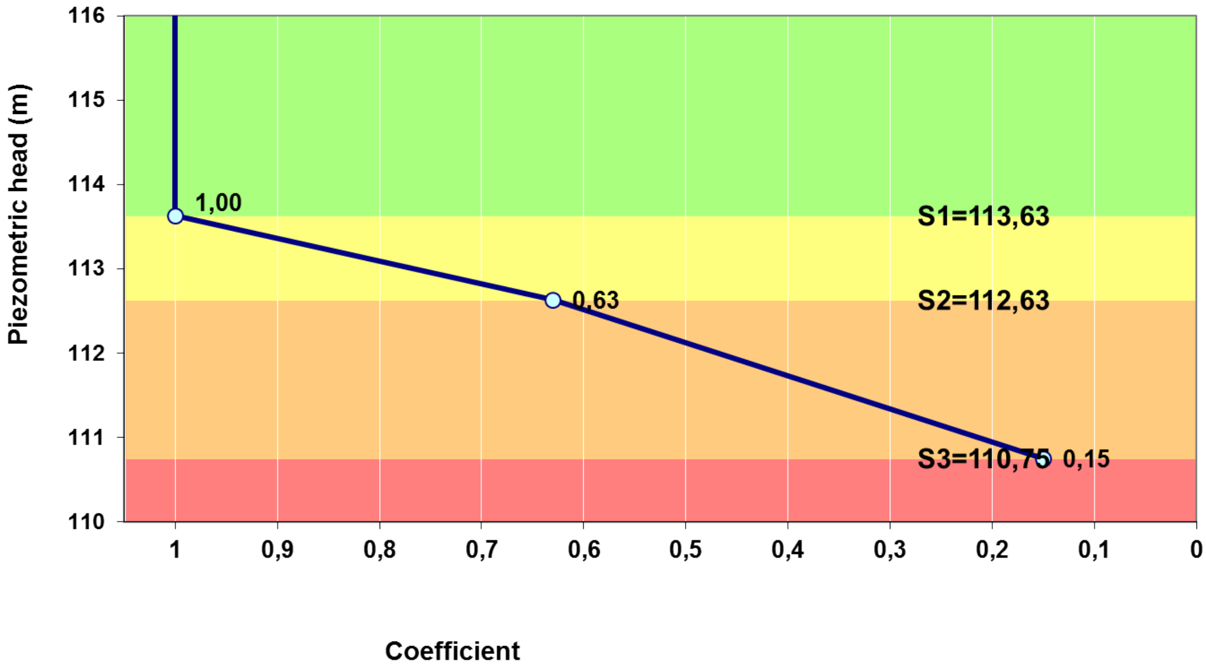


Figure 6.8: Regulatory calculation of the yearly coefficient according to piezometric head since 2010 for the Beauce centrale. Source: DREAL Centre

Variability of piezometric heads according difference random climate scenarios

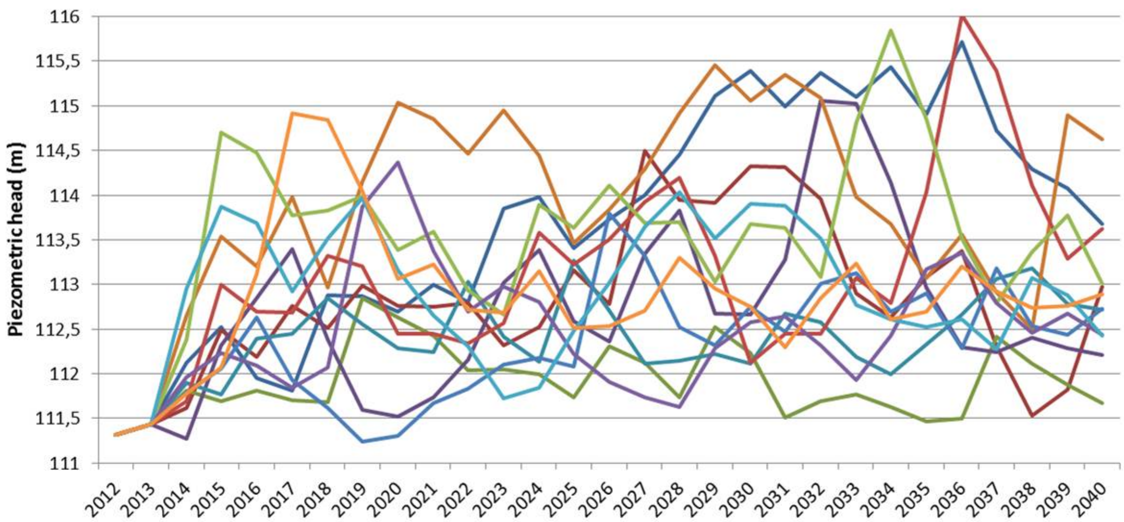


Figure 6.9: Evolution of the piezometric head (meter) for the Beauce centrale calcaire for a few random climate scenarios

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Résumé: Cette thèse développe et discute différentes approches micro-économiques de modélisation de l'agriculture pour représenter l'effet de changements globaux et de politiques de gestion de l'eau sur l'adaptation de l'agriculture et sur les ressources en eau. Après un chapitre de synthèse et une revue de la littérature, quatre essais sont présentés.

Le premier essai décrit la représentation du comportement de dix exploitations agricoles en Alsace et en Bade (Allemagne) à partir de modèles de programmation linéaire qui intègrent la prise en compte du risque. Après extrapolation, les résultats de simulation sont couplés à une chaîne de modèle plante-sol et de transfert hydrogéologique afin d'estimer la concentration future en nitrate dans l'aquifère du Rhin supérieur. Les simulations des trois scénarios de changements - tendanciel, libéral et interventionniste - suggèrent que les concentrations en nitrates baissent dans les trois cas par rapport à la référence.

Le second essai explore l'effet de l'incertitude de changements globaux sur les ressources en eau par des simulations Monte Carlo pour le modèle alsacien (premier essai) et un modèle de demande en eau agricole (Sud-Ouest). Plusieurs niveaux de dépendance entre les paramètres incertains sont caractérisés. L'analyse des résultats montre que les objectifs environnementaux peuvent être déterminés avec suffisamment de précision malgré l'incertitude forte.

Le troisième essai développe un modèle agricole régional de programmation mathématique positive avec élasticité de substitution constante entre l'eau et la terre afin d'explorer comment l'agriculture, partiellement irriguée, de Beauce s'adapte à une baisse de la disponibilité en eau. La réponse du rendement à l'eau est calibrée à partir d'information agronomique. Les adaptations à la baisse de disponibilité en eau sont distinguées selon qu'elles correspondent à des baisses de dose d'eau d'irrigation ou de changement de culture. Environ 20% de la réduction est due à la baisse des doses d'eau (marge intensive).

Le dernier essai présente un modèle hydro-économique "holistic" de l'agriculture et de l'aquifère de Beauce afin d'évaluer plusieurs politiques de gestion quantitatives de l'eau ainsi que d'évaluer le cas où l'accès à la ressource n'est plus régulé. Des simulations dynamiques sont réalisées à l'horizon 2040 en tenant compte de l'incertitude liée au changement climatique. La politique actuelle de quotas annualisés semble être plus coût-efficace que les autres politiques testées (taxes, transferts etc.).

Abstract: This thesis develops and discusses agricultural-supply modeling approaches for representing the adaptation of farming to global changes and water policies: their effects on agricultural economics and water resources comprise critical information for decision makers. After a summary and a review chapter, four essays are presented.

The first essay describes a representation of the behavior of ten typical farms using a risk linear programming model connected to a plant-soil-hydrodynamic model chain, to assess the future level of nitrate contamination in the upper Rhine valley aquifer. The baseline, liberal, and interventionist scenarios for 2015 all result in lower nitrate concentrations.

The second essay explores the effects of the economic uncertainty of global changes by means of a Monte Carlo approach distinguishing various levels of dependence on uncertain parameters. Analyses for a nitrate-oriented and a water-use model (in Alsace and southwestern France) show that the environmental objectives can be targeted with sufficient confidence.

The third essay develops a flexible specification for positive mathematical programming - constant elasticity of substitution with decreasing returns - to explore how irrigated farming adapts to increased water scarcity in Beauce, France. The possibility of adjusting the application of water per hectare accounts for about 20% of the response.

The last essay presents the development of a holistic hydro-economic model of Beauce's agriculture and aquifer under climate-change uncertainty, so as to evaluate various water policies, as well as the open-access case, up to the year 2040. The results show that the baseline policy is more cost-effective than the other instruments tested (tax, transfer, etc.).